Comparative Laboratory Evaluation of Natural Hydraulic Lime Mortars for Conservation

Seo Jun Oh

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Thesis Advisor: Norman R. Weiss
Readers: Jennifer Schork and John J. Walsh

Graduate School of Architecture, Planning and Preservation
Columbia University

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Abstract:

Over the past two decades, natural hydraulic lime (NHL) has become a popular binder in restoration mortars used for the conservation of historic masonry buildings in North America. The most obvious advantage of the NHL mortars is a more rapid setting as compared with non-hydraulic hydrated lime (and lime putty) mortars. At the same time, NHL mortars are said to have the favorable attributes of most lime-based formulations, for example, low-to-medium 28-day strength, and relatively high-water vapor transmissivity (WVT).

The longer-term performance of NHL mortars, however, is difficult to predict, as they are produced from impure limestones quarried at various geographical locations in Western Europe. As the mineralogy of the source rock varies, so does the chemistry of the individual hydraulic lime. Moreover, the scarcity of manufacturers' data and of independent laboratory-based literature on NHL mortars is a very significant issue. The concept of pointing mortar as a building component that is sacrificial and "compatible" – as often discussed for NHLs as for other lime mortars--is difficult to translate into conservation practice in the absence of scientific data. Of course, mortar testing data is only one aspect of those issues, as the behavior of the masonry units would also need to be studied on a building-by-building basis, and in a detailed way to understand "compatibility".

The goal of this research is the examination and comparative evaluation of some fundamental properties of NHL mortars. Eleven NHL binders from four different manufacturers were selected for this study, all of them available in the North American market. More than 200 specimens were prepared with a volumetric (1: 2.25) binder-sand ratio, based on a common mix design for restoration mortars used in the field. For comparison purposes, Type O mortars with a volumetric (1 portland cement: 2.5

hydrated lime: 7.9 aggregate) mix ratio were prepared under the same conditions. Experimental programs were created to study three crucial parameters: compressive strength, water vapor transmission, and water absorption by capillary uptake. The testing programs revealed some interesting data, suggesting that the properties of the subject NHL mortars were relatively independent of the classifications of the binders.

Chapter 1. Introduction

1.1 Mortar for repair of historic masonry

Design and application of restoration mortar requires architectural conservators to consider various criteria, such as aesthetics and performance, both often based on historic composition. If the goal is to select a repointing mortar that does not cause damage to the historic substrate, the mortar should be designed according to specific performance criteria, as the physical and mechanical properties of mortar can greatly affect the durability of the masonry system.[1]

It is frequently said that repair mortars should closely match the historic mortar employed in the original construction. A "like-to-like" approach, however, does not guarantee "compatibility," because a replica of the original mortar could still perform poorly with the masonry units depending on the mortar's properties. For example, now it is widely accepted that cement-based mortars with relatively high strength and low vapor permeability, can cause damage to delicate historic stones.[2] By the 1980s, emphasis had shifted from "like-to-like" replacement to the performance of mortar, which focused on the interrelationship between mortar properties and those of the adjoining masonry.[3] Defining a concept of compatibility has been a subject of

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[1] Hughes, J. and J. Valek. Mortars in Historic Buildings. A review of the scientific and conservation literature. Edinburgh: Historic Scotland, 2003; Papayianni, I. et al. "Study of the Existing Old Mortars of the Cells of Hosios Loukas Monastery and Proposal for Compatible Repair Mortars", Proceedings of 5th International Congress on Restoration of Architectural Heritage, Firenze, 2000.
[2] Robert C. Mack et al. "Repointing Mortar Joints in Historic Masonry Buildings." National Park Service, (1998); Snow, Jessica and Torney Clare, Lime Mortars in Traditional Building, (Edinburgh: Historic Scotland, 2014), 6
[3] Peroni, S. et al. "Lime Based Mortars for the Repair of Ancient Masonry and Possible Substitutes", Proceedings of Mortars, Cements, and Grouts used in the Conservation of Historic Buildings, ICCORM, 1981, 63-100; Pavia S., and O. Brennan. "Portland Cement-Lime Mortars for Conservation." 3rd Historic Mortars Conference: Glasgow, Scotland. (September 2013); Jan Válek et al., "Recommendation of RILEM TC 243-SGM: Functional Requirements for Surface Repair Mortars

discussion by a number of researchers and has been addressed again in the second chapter of this thesis.

When studying compatibility, the interaction between mortar and masonry units needs to be analyzed critically, based on comparison of mechanical, physical, and chemical properties. This often entails complex testing programs.[4] In practice, it is often too difficult to define each property for an ideal conservation mortar, thus the research design is typically based on “general requirements”, such as low mechanical strength, low elastic modulus, higher capillarity and water vapor permeability, and lower soluble salt content.[5]

In this context, Natural Hydraulic Lime (NHL) mortar has emerged in the North American market in the past two decades as an alternative to cement-based mortars with high compressive strength and low vapor permeability. Currently, all NHL binders on the market are made of limestones quarried from various locations in Europe, where local silica and aluminosilicate impurities in the source rock allow mortars to set in the presence of water. NHL products have been marketed to satisfy the general requirements of repair materials, such as being “flexible” enough to accommodate minor movement and allowing water to diffuse through.[6] Many of NHL’s characteristics overlap with those of traditional lime-based mortar, but NHLs have an advantage in faster setting time and good workability, as they are hydraulic. These working properties have become tremendously useful in contemporary conservation projects, where labor typically costs more than materials.

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for Historic Buildings,” Materials and Structures 52, no. 1, (2019): 1-18
[4] Hughes, J. and J. Valek. Mortars in Historic Buildings, 25
[5] Veiga, M. et al. “Lime-based Mortars: Viability for Use as Substitution Renders in Historical Buildings.” International Journal of Architectural Heritage, 4: 177–195, 2010
[6] Gibbons, P. Preparation and Use of Lime Mortars Technical Advice Note 1. Revised Edition. (Edinburgh: Historic Scotland, 2003), 2-4

1.2 Impact of incompatible mortar

When mortar is not “compatible” with the masonry, it means that the interaction between mortar and masonry can change the condition of masonry prone to deterioration. [7] The outcomes of this interaction are determined by the properties of both masonry and mortar as well as the functionality and geometry of the mortars within the masonry construction. Decay mechanism will be varied depending on the context of masonry, so it is crucial to examine the characteristics of both repair mortar and masonry to design an appropriate conservation mortar. For example, lime mortars with high permeability and low strength can be a reasonable choice for repointing low-fired brick or friable sandstone, where the priority is to avoid water being trapped inside the masonry units. This will not be the case if the mortar is used for repointing joints in a granite ashlar wall, where the strength of the repair mortar is not an issue unless it is too weak to maintain the integrity to weathering. In other words, no conservation mortar will be “universally compatible” with a range of different brick and stone types.[8] Each masonry construction has unique properties, and compatibility of mortar should be defined based on the present condition of the surroundings.

Understanding the mechanisms that cause decay to masonry is an essential step to identifying the criteria for an effective conservation mortar. Incompatible mortar can cause distress to the existing material mainly through the repeated interaction of two mechanisms. The first is a moisture transportation mechanism; for example, if the mortar cannot absorb or diffuse moisture properly, moisture will concentrate within the porous units near the mortar joints and cause frost damage during freeze-thaw cycle.[9]

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[7] Veiga, M. et al. Lime-based Mortars.

[8] Torney, Clare et al. “Restoration Mortars in Conservation Work: Considerations & Compatibility”, 3rd Historic Mortars Conference: Glasgow, Scotland. (September 2013)

[9] Gibbons, P. Preparation and Use of Lime Mortars

When it fails to escape through mortar joints, moisture will likely migrate, freeze, and expand within the masonry unit, eventually causing spalling and crumbling of masonry.[10] Entrapped moisture can enable soluble salts to be transferred into the masonry pores, leading to rapid near-surface decay through subsequent salt crystallization and hydration-dehydration cycle.[11] In many situation, it is potentially beneficial for conservation mortars to allow outward vapors transport through the joints.

The second mechanism is based on a differential thermal and hygroscopic expansion behavior between mortar and masonry. Building walls are susceptible to seasonal dimensional changes escalated with a thermal cycling, and the mortar should be able to deform and accommodate this movement.[12] When the mortar is significantly stronger than the adjacent masonry and does not deform, it will concentrate stress to the masonry during expansion and contraction.[13] Repeated cycles of this mechanism may cause cracking and spalling of the masonry, which allows more moisture to penetrate into the wall.[14] To restate a basic point, assessing the appropriate mechanical properties of a conservation mortar is not a simple task and must be determined by factoring in the type and present condition of masonry units, the location of mortar in the building construction, and the geometry of the joint.

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[10] Gibbons, P. Preparation and Use of Lime Mortars
[11] Ibid.
[12] Figueiredo, Cristiano. "Properties and Performance of Lime Mortars for Conservation: The Role of Binder Chemistry and Curing Regime." (PhD diss., University of Bath, Department of Architecture and Civil Engineering, 2018).
[13] Vermeltfoort, A.T. et al. "Thermal Strains in Repointed Masonry: Preliminary Investigations Using ESPI", *Proceeding of RILEM International Workshop, "Historic Mortars: Characteristics and Tests",* held at Paisley, 1999, edited by J.J. Hughes at al., RILEM, 2000, 219-228; Hughes, J. and J. Valek. Mortars in Historic Buildings; Gibbons, P. Preparation and Use of Lime Mortars
[14] Macias, A. et al. "The Deterioration of Mortars in Toledo's Cathedral: Studies on Thermal and Hygric Expansion", Proceedings of 7th International Congress on Deterioration and Conservation of Stone, held at Lisbon, 1992, 1213-1221; Fontaine, L. et al. "Practice and Research: The Need for Standards for Historic Mortars", The Use of and Need of Preservation Standards in Architectural Conservation, West Conshohocken, PA: ASTM, 1999, 158-171; Veiga, M. et al. Lime-based Mortars; Sasse, H. R. and Snethlage, R., 'Methods for the Evolution of stone Conservation Treatments', Report of the Dahlem Workshop on 'Saving our architectural heritage: the conservation of historic stone structures.' Edited by N.S. Baer and R. Snethlage, John Wiley &Sons Ltd. pp. 223-243, 1997.

1.3. Thesis objective

The goal of this thesis is the examination and comparative evaluation of some fundamental properties of NHL mortars for conservation use. For nearly two decades, NHL has been used for repairing historic masonry buildings of North America, but the laboratory-based literatures on NHL is still scarce and the data from the manufacturers is often incomplete. Lack of empirical data is a serious issue, as NHL binders are manufactured from impure limestones, with each a unique chemical composition. Mortar properties tend to vary according to the parent rock composition as well as the calcination temperatures and duration. Furthermore, some recent studies have showed NHL mortars' properties are often variable by brand and independent of classifications when prepared according to the mix design commonly used in building conservation.[15] It is critical to understand the range of physical and mechanical properties of NHL mortars before applying them freely on valuable historic masonry.

Figure 1.1. Binders selected for research

Binder	Place of origin
St. Astier NHL 2	St. Astier, France
St. Astier NHL 3.5	
St. Astier NHL 5	
Otterbein NHL 2	Germany
Otterbein NHL 3.5	
Otterbein NHL 5	
Lafarge NHL 2	Ardèche Valley, France
Lafarge NHL 3.5	
Biolime NHL 2	Northern Italy
Biolime NHL 3.5	
Biolime NHL 5	
Type O mortar	Lehigh white portland cement Carmeuse hydrated lime

[15] Schork et al. "Comparative Laboratory Evaluation of Conservation Mortars", APT Bulletin, Vol. 43, No.1, 2012, 7-14; Henry, Alison et. al. "Hydraulic Lime Production Coming Full Circle?" The Building Conservation Directory, 2018; Figueiredo, Cristiano. "Properties and Performance of Lime Mortars for

Eleven NHL binders from four different manufacturers were selected for this study, all of them now commercially available in North America (Fig. 1.1). More than 200 specimens were prepared with a volumetric 1 : 2.25 binder-sand ratio, based on a mix design for conservation mortars used in the field. Binder-sand ratio of common NHL mortars vary from 1 : 2 to 1 : 3 depending on the project and application. The specific mix was selected in order to make comparisons with other NHL mortar research that used a 1 : 2 and a 1 : 2.25 ratio.[16] In addition to NHL mortars, a Type O mortar with a volumetric (1 portland cement: 2.5 hydrated lime: 7.9 aggregate) mix ratio was also prepared.

Experimental programs were developed to study three important parameters: water vapor transmission, water absorption rate by capillary uptake, and compressive strength. Having data for these parameters is crucial for understanding hygrothermal and mechanical performance of NHL mortars.[17] The main objective of the experiment was to delineate the findings from the testing and analyze the data to determine implications for the performance of NHL mortars for conservation use. Some of the findings from the experiment raised questions that cannot be answered from this thesis alone, and those questions will be considered in the final chapter as a proposed avenue for future research.

Conservation"; Veiga, M. et al. Lime-based Mortars.

[16] 2012 research by Schork et al. used 1: 2.25 mix after consulting with masons with 30-year experience in conservation projects. Figueiredo's 2018 dissertation and Pavia's 2005 publication both used 1: 2 mix ratios for the NHL mortars.

[17] Pavia, S. "Design of Quality, Durable Mortar for the Conservation of Historic Masonry Fabrics." Proceedings of the 6th International Congress: Repair and Renovation of Concrete Structures. Global Construction: Ultimate Concrete Opportunities. Dundee, Scotland, July 2005. Eds R.K. Dhir, M.R. Jones and L. Zheng. Published by Thomas Telford, London. pp. 469-476.

Chapter 2. Literature Review

In this chapter, relevant literature resources, specifications, and laboratory-based research will be discussed, organized into three topics. The first topic examines the lime, portland cement, and NHL mortars and reviews the development history. The second topic addresses the concept of compatibility and its implications with respect to conservation mortar. The third part of this chapter reviews existing industry specifications and laboratory-based data on NHL mortars, which has been used as a particularly valuable reference for this thesis.

2.1. Lime, portland cement, and NHL mortars

The earliest evidence of lime used as a building material dates back to about 8,000 BC.[18] The use of lime mortar became mainstream after about 1,000 BC, when it was adopted by the Greeks.[19] They were arguably the first to find the advantage of the hydraulic properties of some lime mortars while constructing a water channel in Olympia during 7th century BC.[20] By the first century BC, lime mortars were widely used by Greek and Roman builders. In De Architectura, Roman architect Vitruvius suggested the use of additives for improving the composition of lime mortars.[21] The Romans pioneered the technology of hydraulic lime mortars by experimenting with various additives. They understood the advantage of hydraulicity for mortar and addressed this

[18] Dorn Carran , John Hughes , Alick Leslie & Craig Kennedy (2012) “A Short History of the Use of Lime as a Building Material Beyond Europe and North America”, International Journal of Architectural Heritage, 6:2, 117-146
[19] Ibid.
[20] Hughes, J. and J. Valek. Mortars in Historic Buildings, 6
[21] Artioli, Gilberto et al. “The Vitruvian legacy: mortars and binders before and after the Roman world” EMU Notes in Mineralogy, Vol. 20 (2019), Chapter 4, 151–202

need by adding crushed bricks, tile, and the volcanic ash called pozzolana. The Vitruvian tradition, however, emphasized the use of pure white limestone as a basis for producing lime mortars, and demonstrated that the Romans did not understand the presence of natural clay impurities in some limestones could create mortars that were hydraulic.[22] Until the early 18th century, it is said that lime mortars with hydraulic properties were produced from nearly pure limestone and pozzolanic additives, following the Greek and Roman tradition.[23] There are some instances of early use of NHL in the castles and bridges in Central Europe during 14th century, but the production most likely was a result of accidental firing of impure limestone.[24]

In 1756, English engineer John Smeaton investigated the role of clay impurities in the hydraulic properties of some limes.[25] At the time, Smeaton was involved in the construction of the Eddystone Lighthouse and needed a mortar that could withstand the marine environment.[26] Unlike the contemporary architects who still sought white limestones as a better raw material for mortars, he departed from the tradition and experimented with the local Blue Lias limestone with clay impurities. Smeaton's experiment is known as the first example that a limestone with clay impurities could be intentionally selected for manufacturing a hydraulic binder.[27] This event marked a significant change in the development of lime technology and triggered the search for

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[22] Dorn Carran, et al. "A Short History of the Use of Lime as a Building Material Beyond Europe and North America"
[23] Hughes, J. and J. Valek. Mortars in Historic Buildings. A review of the scientific and conservation literature
[24] Artioli, Gilberto et al. "The Vitruvian legacy: mortars and binders before and after the Roman world,177: These 14th century examples are Gothic Obrany Castle in Moravia and Charles Bridge in Prague, Czech Republic.
[25] Eddystone Lighthouse, Smeaton Tower substructure". Engineering Timelines. Retrieved 31 November 2019; McKee, Harley J. Introduction to Early American Masonry - Stone, Brick, Mortar and Plaster. National Trust for Historic Preservation, Columbia University, 1973, 68; Artioli, Gilberto et al. "The Vitruvian legacy: mortars and binders before and after the Roman world,177
[26] Artioli, Gilberto et al. "The Vitruvian legacy: mortars and binders before and after the Roman world"
[27] McKee, Harley J. Introduction to Early American Masonry

new kinds of hydraulic binders.

In 1818, Louis Vicat identified that the hydraulicity of heated impure limestone is directly related to the presence of reactive alumina and silica from the clay.[28] Vicat's published experiments led him to develop five classifications of lime according to its hydraulic quality, which was highly influential in the development of a classification system of natural hydraulic lime.[29]

- Fat lime: does not set under water and dissolves entirely by water
- Lean lime: does not set under water but dissolves only partially
- Moderately hydraulic lime: set under water but hardens slowly
- Hydraulic lime: set under water after 6 or 8 days and continue to harden
- Eminently hydraulic lime: set under water after only 2 or 3 days

By the early twentieth century, the chemistry behind the setting of hydraulic lime was better defined, and more sophisticated classification systems and test standards had emerged. In his 1905 publication, Eckel investigated the chemical composition of different types of limestones and analyzed how the proportion of SiO_2, Al_2O_3, Fe_2O_3, and CaO in the rock affect hydraulic properties of lime. He classified hydraulic limes according to the 'cementation index (CI)', a formula associated with the development of portland cement industry.[30] Eckel used CI to simplify Vicat's classifications into two classes; feebly hydraulic lime with 0.3~0.7 CI and eminently hydraulic lime which has 0.7~1.1 CI. The method of using CI for classification was adopted by other researchers as well, who sometimes used a three-part classification: 'feebly (0.3~0,5), moderately (0.5~0.7), and eminently (0.7~1.1) hydraulic.[31] In addition, Eckel's publications

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[28] Hughes, J. and J. Valek. Mortars in Historic Buildings, 6
[29] Vicat, L., Mortars and Cements. Translated by J. T. Smith,1837, Donhead Publishing, 1997
[30] Eckel, Edwin C., Cements, limes, and plasters; their materials, manufacture, and properties. New York, J. Wiley & sons, inc.; 1902. pp 175-185
[31] Boynton, R.S., Chemistry and Technology of Lime and Limestone, John Wiley and Sons Ltd., 2nd

emphasized that the hydraulicity of lime can be changed by the calcination temperature and duration.[32]

Different types of hydraulic binders were patented, having emerged during the first half of the 19th century.[33] Those hydraulic binders include so-called Roman cement and portland cement in the UK and natural cement in the US.[34] By the early 20th century, portland cement mortar was considered to have superior strength and water resistance, and quickly replaced lime mortar in various applications including the repair of historic buildings.[35] Lime mortars were still used on many occasions, but they were often gauged with cement for durability and faster setting.[36]

2.2. Compatibility

By the 1980s, historic buildings repaired with cement-based mortars were reported to have experienced accelerated deterioration, associated with an incompatibility between mortar and masonry. Consequently, the issue of compatibility received much attention with discussions of the favorable attributes of lime mortars. In 1981 ICCORM conference on historic building conservation, Peroni et al. presented the problems of portland cement mortars and recommended traditional lime mortar as an alternative for conservation.[37] In 1995, Historic Scotland published a technical note that

edition. 1980

[32] Elsen, Jan & Van Balen, Koenraad & Mertens, Gilles. Hydraulicity in Historic Lime Mortars: A Review, 2012

[33] Artioli, Gilberto et al. "The Vitruvian legacy: mortars and binders before and after the Roman world"

[34] Ibid.; Mckee, J. Harley. Canvas White and Natural Cement, 1818-1834. University of California Press, 1961, 194-197.

[35] Snow, Jessica and Torney Clare, Lime Mortars in Traditional Building, 6.

[36] Ibid.

[37] Peroni, S. et al. "Lime Based Mortars for the Repair of Ancient Masonry and Possible Substitutes", Proceedings of Mortars, Cements, and Grouts used in the Conservation of Historic Buildings, ICCORM,

illustrated lime mortar preparation methods. It has become an influential source for promoting the use of lime mortars in conservation projects. [38]

The concept of compatibility has been a frequent subject of conservation literature, but its definition can be difficult to understand when it comes to mortar. It is critical to have a clearer definition of compatibility before evaluating the performance of the NHL mortars studied in this thesis. To start, conservation guidelines from international organizations put an emphasis on theoretical and ethical compatibility, such as respecting original materials and avoiding changes to cultural significance.[39] Such a philosophical point of view may lead to the conclusion that a compatible mortar is simply a copy of the original mortar. This "like-to-like" approach should not be the definition of compatible conservation mortar as it neglects the evaluation of the physical, mechanical, and chemical interactions between mortar and masonry units.

In common conservation practice, masonry materials are preserved while the mortar is replaced. The functions of the repair mortar are to provide stable mortar beds for the masonry and to act as a sacrificial material for the historic masonry unit, while maintaining a reasonable durability.[40] From a functional stand point, Teutonico et al. and Van Hees both presented simplified versions of compatibility as a treatment for material that does not cause damage to the original.[41] Researchers like Sasse and Snethlage delved deeper into the behavior of the repair materials and defined tolerance

1981, 63-100

[38] Gibbons, P. Preparation and Use of Lime Mortars, Technical Advice Note 1

[39] 'Venice Charter', International Charter for the Conservation and Restoration of Monuments and Sites. ICOMOS, 1964; 'Bura Charter', The Australia ICOMOS Charter for the Conservation of Places of Cultural Significance. ICOMOS, 1994

[40] Hughes, J. and J. Valek. Mortars in Historic Buildings, 21

[41] Teutonico, J.M. et al. "A Comparative Study of Hydraulic Lime-Based Mortars", Proceeding of RILEM *International Workshop, "Historic Mortars: Characteristics and Tests",* held at Paisley, 1999, edited by J.J. Hughes at al., RILEM, 2000, 339-349; Van Hees, R.P.J., "Damage Diagnosis and Compatible Repair Mortars", Proceedings of RILEM International Workshop, "Historic Mortars: Characteristics and Tests", held at Paisley, 1999, edited by J.J. Hughes at al., RILEM, 2000, 27-36

limits of the material properties that could ensure compatibility.[42] (Fig. 2.1)

Figure. 2.1: Proposed requirement (as a % of substrate) to evaluate compatibility

Property	Requirement (after one year)
Dynamic Elastic modulus	20~100% (60)
Compressive strength	20~100% (60)
Thermal dilation coefficient	50~150% (100)
Water uptake coefficient	50~100%
Water vapor resistance	50~100%
Pull-off strength	0.5 ~0.8% of stone

In this regard, the definition of comparability should lead to the technical requirements of mortar properties in relation to its surrounding masonry. Peroni et al. argued that understanding the properties of the masonry unit should be the first step to define compatibility and to ensure appropriate selection of mortars.[43]

A body of empirical studies points out that mortars which cause adverse effects typically possess low capillarity, poor adhesion, and excessive mechanical strength.[44] When addressing the performance of conservation mortar, compatibility should at least describe these general properties, and preferably define the technical requirements of both mortar and masonry. For this reason, new materials should not be excluded and can be used for conservation mortar as long as there is clear understanding of their properties.[45] Therefore, NHL, which has not yet been widely used as a typical binder material in historic mortars in North America, deserves a more thorough investigation and evaluation for compatibility in the development of conservation mortars.

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[42] Sasse, H. R. and Snethlage, R., 'Methods for the Evolution of stone Conservation Treatments',
[43] Peroni, S. et al. “Lime Based Mortars for the Repair of Ancient Masonry and Possible Substitutes
[44] Hughes, J.J. "The role of mortar in masonry: An introduction to requirements for the design of repair mortars", Materials and Structures, Vol. RILEM TC 203-RHM, no. 45, 2012, 1287-1294.
[45] Peroni, S. et al. “Lime Based Mortars for the Repair of Ancient Masonry and Possible Substitutes”

2.3. Specifications and laboratory data for NHL mortars

Most NHL products available on the market follow the specification according to the European Standard for Building Lime, EN 459. The standard classifies hydraulic limes in three sub-categories, which are natural hydraulic lime (NHL), hydraulic lime (HL), and formulated lime (FL). The main difference of NHL versus other subcategories according to BS EN 459 is that an NHL should not contain additives, while HL and FL can have additives such as pozzolans, cement, slag, and limestone filler.[46]

EN 459 divides NHL into three classes, NHL 2, NHL 3.5, and NHL 5 based on the 28-day compressive strength of a standard mortar prepared and tested according to EN 459. Each numerical designation of three classes represents the minimum requirement of 28-day compressive strength in megapascals (Fig. 2.2).[47] In the US, there is a related American Society for Testing and Materials (ASTM) standard that refers to NHL, ASTM C141.[48] Unlike EN 459, ASTM C141 does not have three classes and requires hydrated hydraulic lime to have a 28-day compressive strength between 1.7 MPa (250 psi) and 10.3 MPa (1500 psi). Given that all NHL products are quarried and manufactured in Europe, NHL products available in the North American market

Figure. 2.2. Compressive strength requirement for NHL

	7 day strength (Mpa)	28 day strength (Mpa)	Final Setting (h)
NHL 2	-	≥ 2 to ≤ 7	≤ 40
NHL 3.5	-	≥ 3.5 to ≤ 10	≤ 30
NHL 5	≥ 2	≥ 5 to ≤ 15	≤ 15

[46] CEN, BS EN 459-1: 2015, Building Lime, Part 1 Definitions, Specifications and Conformity Criteria. British Standard Institution
[47] CEN, BS EN 459-2: 2015, Building Lime, Part 2 Test Methods. British Standard Institution
[48] ASTM International. C141/C141M-14 Standard Specification for Hydrated Hydraulic Lime for Structural Purposes. West Conshohocken, (PA; ASTM International, 2014)

comply with EN 459.

There has been a concern among members of the conservation community regarding the utility of EN 459 as a tool for selecting binders for conservation mortar.[49] The first issue is that the specification for NHL was established based on the norms of the portland cement and concrete industry and does not necessarily address the requirements relevant to lime mortars. Specifications for hydraulic lime were first included in the EN 459 after 1994, and the approach was directly borrowed from pre-existing specifications for cement.[50] Minimum strength requirements at 28 days are typical parameters for evaluating concrete and cement-based mortars, which acquire most of their strength at 28 days and are mainly being used for structural purposes. Unlike portland cement mortar, NHL mortar will gain strength more slowly at varying rates, and it is very unlikely that NHL mortars will be used for structural purposes.[51]

Moreover, it is questionable that compressive strength can be indicative of the general physical properties of NHL mortars. EN 459 only specified the testing methods for compressive strength and water retention, hence most technical data sheets from the manufacturers do not address other important properties, like vapor permeability or capillarity. Finally, current minimum compressive strength requirements can be misleading, as high strength can be a disadvantage for the conservation purpose of NHL mortars. Based on EN 459, there is no problem for NHL 2 being stronger than NHL 5, as long as standard mortar exceeds the minimum strength requirement. In theory, practitioners may end up using stronger mortars on delicate historic masonry

[49] Figueiredo, Cristiano. "Properties and Performance of Lime Mortars for Conservation"; Henry, Alison et. al. "Hydraulic Lime Production Coming Full Circle?"
[50] CEN, DD EVB 459: 1994, Building Lime, BS EN 459-2: 2015, Building Lime, Part 2 Test Methods; CEN, BS EN 196: 2015, Methods for testing cement
[51] Figueiredo, Cristiano. "Properties and Performance of Lime Mortars for Conservation"

which requires a weaker repair mix design.

Another issue regarding EN 459 is the relevance of the standard mortar for evaluating mechanical properties.[52] Current EN 459 does not specify binder-sand ratio of standard mortar by volume or weight, and only specifies the water-binder ratio, based on the density of each binder. As a result, some researchers have argued that the standard mortar prepared according to EN 459 shows “unworkable consistency” and does not reflect the characteristics of real mortar.[53] Nevertheless, most of the technical data supplied by the manufacturers only reveals the 28-day compressive strength based on the EN 459 standard mortar.[54] This issue regarding difference between the standard mortar and the real mortars used in the field will be addressed further in the Chapter 3.

A number of studies have already shown that NHL mortars tend to show discrepancies with the classification and data supplied by manufacturers.[55] In 2018, Henry et al. examined the inconsistency of NHL's properties and questioned the utility of EN 459 as a testing standard. Different batches of NHLs from the same manufacturer were mixed and tested in two different laboratories under the compliance of EN 459.[56] The result was surprising; several standard mortars failed to passed the minimum strength requirement and data from the two locations were significantly different.[57] In his 2018 dissertation, Figueiredo illustrated that the Otterbein NHL 2 mortars mixed at 1:

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[52] CEN, BS EN 459-2: 2015, Building Lime, Part 2 Test Method; Figueiredo”

[53] Henry, Alison et. al. “Hydraulic Lime Production Coming Full Circle?”; Cristiano et al. “Mechanical Properties of Standard and Commonly Formulated NHL Mortars Used for Retrofitting”

[54] See Appendix B.

[55] Figueiredo, Cristiano. “Properties and Performance of Lime Mortars for Conservation”; Schork et al. “Comparative Laboratory Evaluation of Conservation Mortars”; Henry, Alison et. al. “Hydraulic Lime Production Coming Full Circle?”

[56] Henry, Alison et. al. “Hydraulic Lime Production Coming Full Circle?”

[57] Ibid.

2 volumetric ratio had a higher compressive strength than Otterbein NHL 3.5 and 5 after 90 days of curing. Schork et al. also reported that NHL 3.5 and NHL 5 mortars mixed at a 1: 2.25 ratio showed virtually the same compressive strength after five months of curing.

A review of specifications, manufacturer's data, and laboratory literature has underlined the necessity of comparative laboratory data to evaluate the behavior of NHL mortars. Current specifications and test standards seem to encourage manufacturers to generate uninformative data, and the classification criteria of EN 459 can thus be misleading for the selection of conservation mortar. Significant inconsistencies in published data suggest that due diligence is required for assessing the general compatibility requirement of NHL mortars.

Chapter 3. Experiment Program

3.1. Sample preparation protocol

Defining step-by-step experimental procedures is important for creating reliable data, understanding it, and relating that data to the mortar properties. Sample preparation protocols were developed based on EN 459, with adjustments to the mix. For the apparatus and testing procedures not specified in EN 459, relevant ASTM standards were referenced. Each specimen was labeled based on the manufacturer and class as illustrated in Fig. 3.1. All specimens were prepared by the author alone to eliminate a variable caused by preparation technique. Before making actual specimens, the procedures were demonstrated to Jennifer Schork, a senior conservator at Integrated Conservation Resources, Inc., to ensure the integrity of the process.

Figure. 3.1: Binders and abbreviations

Binder	Abbreviation	Place of origin
St. Astier NHL 2	SA 2	St. Astier, France
St. Astier NHL 3.5	SA 3.5	
St. Astier NHL 5	SA 5	
Otterbein NHL 2	OB 2	Germany
Otterbein NHL 3.5	OB 3.5	
Otterbein NHL 5	OB 5	
Lafarge NHL 2	LF 2	Ardèche Valley, France
Lafarge NHL 3.5	LF 3.5	
Biolime NHL 2	BL 2	Northern Italy
Biolime NHL 3.5	BL 3.5	
Biolime NHL 5	BL 5	
Type O mortar	T/O	Lehigh white portland cement Carmeuse hydrated lime

3.1.1. Mix design

All mortar specimens were based on a volumetric 1: 2.25 binder-sand ratio, which is a commonly used mix ratio in conservation mortars. As mentioned, above, this mix ratio does not comply with the standard mortar according to European standards, as the goal of this thesis testing was to compare and evaluate the NHL mortars actually used in conservation projects. The most current version of European standard does not define the binder-sand ratio for standard mortar composition. Instead, the standard defines a water-binder ratio based on the bulk density of NHL, which is not a method for mixing the mortars used in the field (Fig. 3.2).[58] Based on EN 459 specification, laboratories across Europe use 1: 3 binder-sand ratio by weight to make standard mortar.[59] Depending on the bulk density of binders, 1 : 3 by weight will be equivalent to only 1 part NHL to 1.3~1.6 part sand by volume. In field practice, mix will always be measured in volumetric proportions, and the common range is 1 part NHL to 2 to 3 parts of sand by volume.

Figure. 3.2: Water-binder ratio of standard mortar based on EN 459

Type of Product	Bulk density (kg/dm$^{3)}$	water binder ratio	mass of water
NHL 2, 3.5	≤ 0.6	0.6	270 ± 2
NHL 2, 3.5	> 0.6	0.55	248 ± 2
NHL 5	> 0.6	0.5	225 ± 2

* 0.6 kg/dm^3 = approx. 37.5 pcf.

[58] CEN, 2010b. EN 459-2:2010 - Building lime. Test methods., 57
[59] Figueiredo, Cristiano. “Properties and Performance of Lime Mortars for Conservation”, 34

Figure 3.3: Vicat consistency apparatus

Figure 3.4: Electric mixer

Determining the water-binder ratio and the workability of specimens was a crucial component of the experimental program. In practice, workability is determined by skilled craftspeople, and craftsmanship alone will control the water-binder ratio of the mortar.[60] Vicat consistency apparatus with 17.5mm plunger was utilized during sample preparation (Fig. 3.3). Both EN 459 and ASTM C807 acknowledge the Vicat apparatus as a method for testing the consistency of mortar, and 2012 research by Schork et al. on conservation mortars also showed that the Vicat apparatus can be a reliable tool for quantifying the water-binder ratio.[61] After numerous tests and trials, water-binder ratios for each binder were determined to achieve 3~5 mm of plunger penetration.

[60] Hughes, J. and J. Valek. Mortars in Historic Buildings, 64
[61] CEN, EN 459-2:2010 - Building lime. Test methods., 37; ASTM International. C807-18 Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle; Schork et al. “Comparative Laboratory Evaluation of Conservation Mortars”

Finally, samples of Type O mortars made of white portland cement and calcitic hydrated lime were prepared for comparison. Type O mortar has been widely used for conservation projects of North America due to its good workability and relatively low strength compared to other cement-lime-based mortars with higher portland cement content.[62] Specimens were prepared as per the ASTM C270 standard with 1: 2.25 mix, the same binder-sand ratio as the NHL mortars. 1: 2.25 is the least amount of sand allowed as per this ASTM standard and not a commonly used ratio for Type O mortar, but the goal here was to have a comparable reference with NHL mortars.[63] For the binder formula, 1 part white portland cement to 2.5 part lime was adopted, which is the largest amount of lime proportion allowed for Type O mortar.[64] Total volumetric mix ratio for Type O mortars was 1: 2.5 : 7.9 (portland cement : hydrated lime : sand).

Figure 3.5: NHL mortar formulation

NHL	Density (pcf)	Binder (g)	Sand (g)	Water(g)	W/B (w/w)	Sand/Binder (w/w)	Vicat (mm)
SA 2	31.2	249.6	1440	290	1.16	5.77	3
SA 3.5	40.6	324.8	1440	300	0.92	4.43	4
SA 5	43.7	349.6	1440	310	0.89	4.12	4
OB 2	31.2	249.6	1440	300	1.20	5.77	3
OB 3.5	34.3	274.4	1440	290	1.06	5.25	3
OB 5	34.3	274.4	1440	290	1.06	5.25	4
LF 2	38.1	304.8	1440	300	0.98	4.72	4
LF 3.5	36.8	294.4	1440	300	1.02	4.89	3
BL 2	38.6	308.8	1440	300	0.97	4.66	5
BL 3.5	40	320	1440	305	0.95	4.5	3
BL 5	48	384	1440	290	0.76	3.75	5

Figure 3.5 shows the detailed composition of NHL mortar formulas prepared in this thesis. To ensure the reproducibility of the experiment, mortar formulations were determined based on the bulk density of the individual binders, provided by the

[62] ASTM International. C270-19 Standard Specification for Mortar for Unit Masonry; Pavia S., and O. Brennan. “Portland Cement-Lime Mortars for Conservation.”
[63] ASTM International. C270-19 Standard Specification for Mortar for Unit Masonry
[64] Ibid.

manufacturers. NHL binders have bulk densities ranging from 31.2 pounds per cubic feet (PCF) to 48 PCF. St. Astier NHL 2 and Otterbein NHL 2 are of low density, so the mortars contain less binder by weight, and needed to be mixed with more water than some NHL 3.5 or NHL 5 mortars. On the contrary, Biolime NHL 5 has a higher bulk density than the 2 and 3.5 and require a smaller amount of water for obtaining desired consistency. NHL 2 and NHL 3.5 from Lafarge and Biolime have similar bulk density, so their water-binder ratios were not so different.

3.1.2. Aggregate

Well-graded white masons' sand was purchased from Geo. Schofield Co. Inc. The sand is local to New Jersey and complies with ASTM C144.[65]

3.1.3 Laboratory environment and mixing procedure

All specimens were produced at the Preservation Technology Laboratory at Columbia University, between October 2019 and March 2020. Throughout this period, the laboratory environment was maintained at a temperature of 22 ± 2 °C and a relative humidity of 38 ± 5%. The relative humidity of the lab was lower than the EN 459-2 standard which states that the relative humidity of the laboratory should be not less than 50%.[66] The amount of aggregate for each batch was limited to 1,440 grams. Total mixing time did not take longer than 5 minutes and each batch was mixed with a heavy-

[65] ASTM International, "Standard Specification for Aggregate for Masonry Mortar," ASTM C 144-04 (West Conshohocken, Penn.: ASTM, 2019)
[66] CEN, EN 459-2:2010 - Building lime. Test methods.

duty electric mixer (Fig. 3.4) All of the NHL and half of the sand were introduced to a dry stainless-steel mixing bowl and mixed at low speed for 30 seconds. Then, the rest of the sand was poured into the mixing bowl and mixed again at a low speed. While continuing to mix the dry component, water was added slowly for the next three minutes. Two minutes after adding water, the mixer was stopped for 30 seconds to scrape mortars adhered to the bowl, and mixing was then resumed.

3.1.4. Compressive strength specimens

Compressive strength specimens were cast in a two-inch by two-inch cube mold. Six sets of three-gang molds were used to make strength test specimens, of which five of them were made of plastic and one of stainless steel. ASTM C109 defines the material of cube molds to be metal, so the plastic cube molds did not meet the requirement of ASTM (Fig. 3.6).[67] Nevertheless, the plastic molds had the dimensional tolerance specified by ASTM C109 and have planar surfaces which are adequate enough to produce sharp-edged cubes. Compaction of the mortars was done by Teflon tamping rod as per the methods illustrated in ASTM C109.[68] Once molding was done, specimens were sealed in a damp plastic bag for 48 hours, until they were demolded

Figure 3.6. Cube molds for compressive strength testing

[67] ASTM International. C109/C109M-20a Standard Test Method for Compressive Strength of Hydraulic Cement Mortars. West Conshohocken, PA; ASTM International, 2020
[68] CEN, EN 459-2:2010 - Building lime. Test methods

and moved to a high humidity chamber. Six cube specimens were prepared per each of the NHL binder types for 28 days and another 90 days. For Type O mortars, three specimens were prepared for each test age. A total of 138 cube samples were produced for compressive strength testing.

3.1.5. Water vapor transmission (WVT) specimens

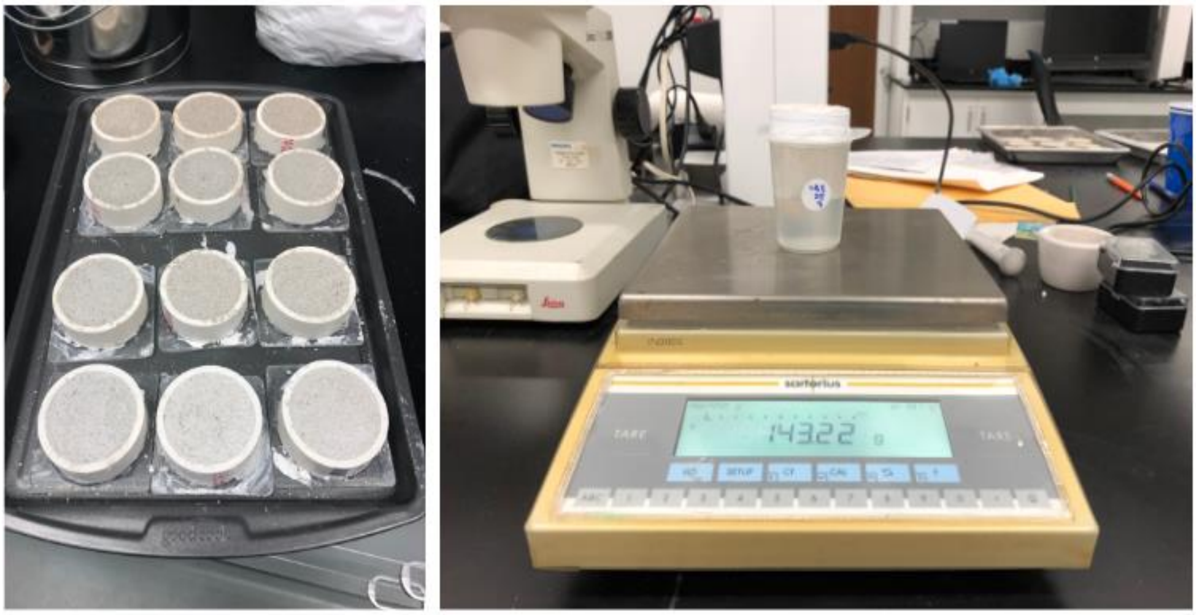
PVC ring molds were used for casting disk samples with a 2-inch diameter and ¾ inch thickness. Freshly made disks were placed in a moist plastic bag for 24 hours then cured at a relative humidity (RH) not less than 90%. When the curing was done, each surface was dried at ambient temperature for 24 hours. Dish assemblies were prepared based on the ‘water method’ of ASTM E96 as illustrated in Weiss and Jacob’s 1989 publication on WVT.[69] Perimeter edges of the disks was wrapped with Teflon tape and attached to a tri-cornered 100 ml plastic beaker, to which 50ml of distilled water had been added. Intersection of the mortar disk and the beaker was tightly sealed with an epoxy resin (Fig. 3.7).

Three disk specimens were prepared for each of 12 test groups and tested after 45-days of curing. The water level of dish assembly failed to comply the ASTM E96. ASTM E96 “water method” specified that water level inside the cup should be within 19 ± 6 mm from the specimen to restrain vapor resistance. With 50ml of water, the initial water level was 22 mm from the specimen and dropped to 27 mm by the end of

[69] ASTM International. E96/E96M-16 Standard Test Methods for Water Vapor Transmission of Materials. West Conshohocken, PA; ASTM International, 2016; Weiss, R. Norman and Judith Jacob “Laboratory Measurement of Water Vapor Transmission Rates of Masonry Mortars and Paints”, APT Bulletin: The Journal of Preservation Technology, Vol. 21, No. 3/4 (1989), pp.62-70

measurement. This assembly preparation error was noted later, after the data collection was completed.

Figure 3.7: Disk mortars and dish assembly for WVT specimens



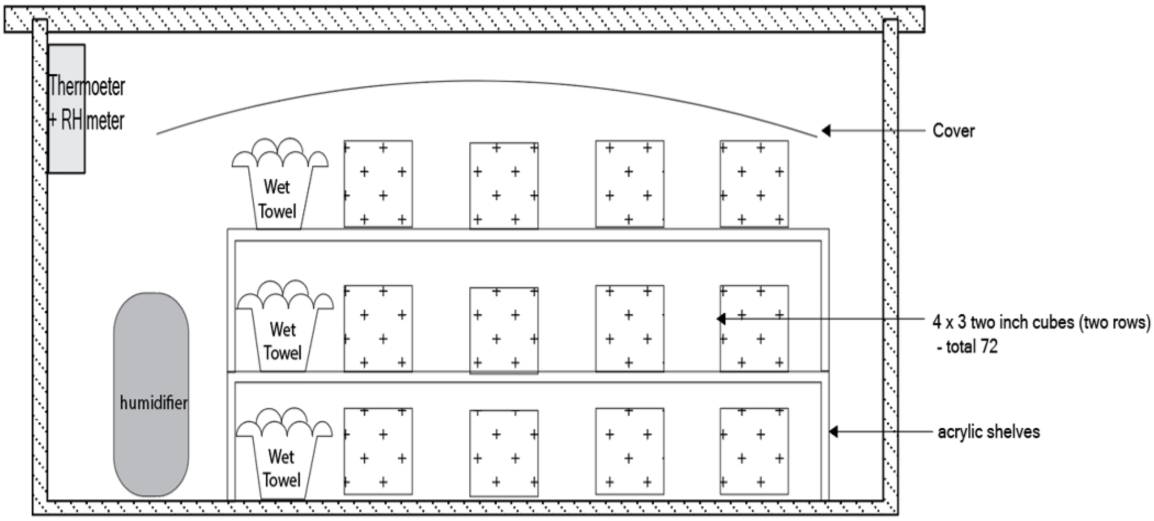
3.1.6. Water absorption specimens

Two-inch cube specimens were prepared to investigate water absorption rate by capillary uptake. Cubes were cast in disposable cube liners and went through the same preparation and curing procedure for the strength and WVT specimens. After curing, cubes were oven dried at 80±20 °C for 20 hours and cooled an additional 4 hours in the ambient environment. A total of 36 cubes were prepared, three cubes per the 12 test groups for 90 days curing.

3.2. Curing protocol

Maintaining a consistent curing environment was a crucial part of research. Three custom-made moisture cabinets were created to an environment of at least 90% relative humidity throughout the curing period. Portable humidifiers and wet clothes were used to maintain the RH of the cabinet. A series of trial and error tests showed that periodic misting was also required. (Fig. 3.8). For the first 14 days, each sample was directly misted with a sprayer once every day in addition to the 8 hours of misting from the humidifier. After 14 days, mortars were cured with the humidifier alone and stayed at the humidity chamber until the testing date. Two thermometer/hygrometers were placed in each cabinet, one at the bottom surface and one on the top shelf, to monitor the daily change of RH and temperature.

Figure 3.8: Section of high humidity chamber



3.3. Testing protocol

3.3.1. Compressive strength testing

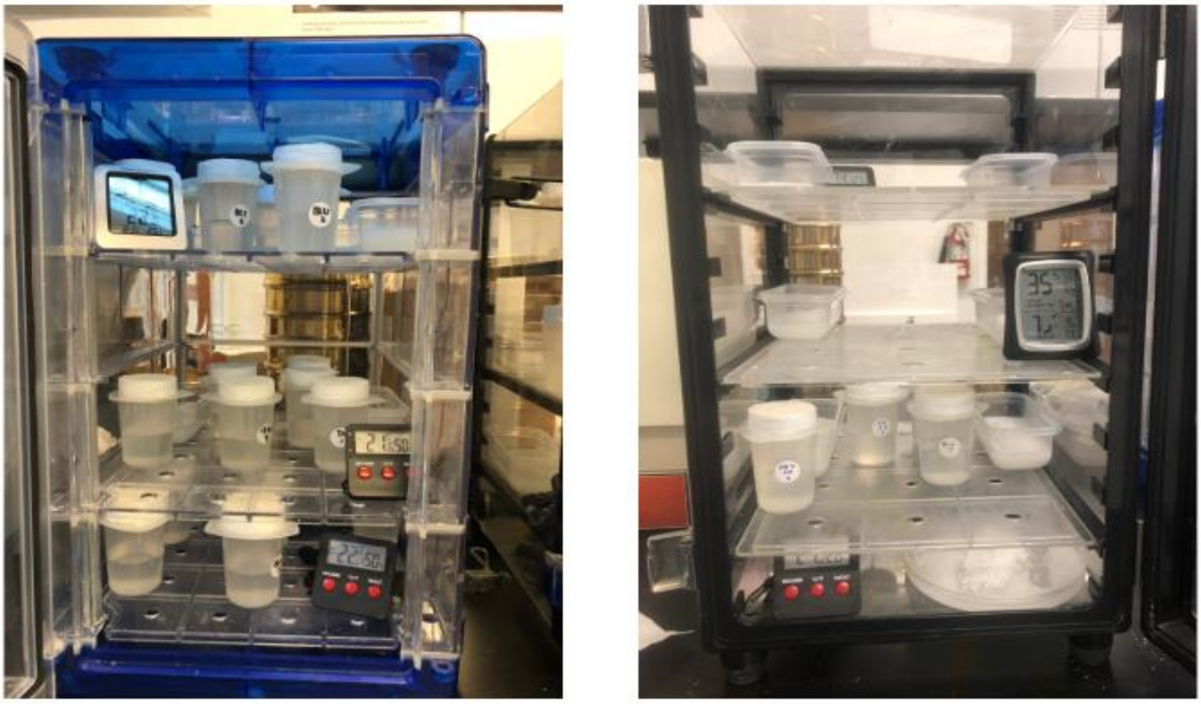
Six specimens were tested and averaged to represent the compressive strength of each NHL binder group. Data were subsequently Q-tested to verify precision and reject outliers. Gathered data were in a relatively tight range and no eliminations were made. All testing was carried out at Highbridge Materials Consulting, Inc. in Pleasantville, New York. (Fig. 3.9) For the weaker NHL mortars with a compressive strength less than 1,000 PSI, a lower-range calibrated load cell was installed to accommodate the lower strength of the test samples. All strength testing was performed under the guidance of experienced laboratory technicians at Highbridge.

Figure 3.9: Compressive strength machine and specimens

3.3.2. Water vapor permeability

Test environments for WVT testing were created at the Preservation Technology Laboratory of Columbia University. Two desiccator cabinets each with a 2.0 cubic foot capacity were modified to provide the WVT testing environment specified in ASTM E96.[70] 36 dish assemblies were divided into two sets and placed in the desiccator cabinets after 45 days of curing. To maintain the RH around 50%, magnesium nitrate dishes were introduced into the cabinets, to theoretically maintain 53% RH at 20~25°C temperature .[71] Magnesium nitrate was divided into smaller portions, soaked in distilled water, and placed on every shelf along with a hygrometer. In addition, a small (80x80 mm) computer fan was attached at the bottom of each of the cabinets to provide convection. (Fig. 3.10) The weight of each dish assembly was measured at 24 ± 2

Figure 3.10: Desiccator chamber for WVT testing



[70] ASTM International. E96/E96M-16 Standard Test Methods for Water Vapor Transmission

[71] Greenspan, Lewis. "Humidity Fixed Points of Binary Saturated Aqueous Solutions", JOURNAL OF RESEARCH of the National Bureau of Standards - A. Physics and Chemistry Vol. 81 A, No.1, 1977, 1-8

hour intervals for 30 days. The locations of each specimen inside the cabinet were changed randomly throughout the testing period to avoid systematic error. Temperature and RH of each shelf was recorded every day. During the initial stage, RH inside the cabinet ranged from 54% to 58%, but after four days of observation, an average RH of 48~52% was reached, and the changed remained at the lower level.

3.3.3. Water absorption by capillary uptake

Figure 3.11: Water absorption testing environment

The water absorption testing in this research followed the standards defined in ASTM C1403. Measurement was done as an average of three cubes cured for 90 days.[72] A plastic container with a capacity of 10.25 gallons and 30 x 13 x 5” inner dimensions was selected for the test. Stainless steel mesh with 1-inch base was used

[72] ASTM International. C1403-15 Standard Test Method for Rate of Water Absorption of Masonry Mortars. West Conshohocken, PA; ASTM International, 2015

for specimen support. Distilled water was poured into the container until the water level reached 3 mm above the mesh surface. (Fig. 3.11) After measuring the dimension of the contact surface and the dry weight the cube, the specimens were put into water, and the weight was measured at 1, 3, 5, 15, 30 minutes, 1 hour, 2 hours, 4 hours, 6 hours, 8 hours, and 24 hours. Testing was considered finished and no further measurements were taken once the moisture reached the top of the specimen. Finally, the weight of the water absorbed per unit area (g/cm^2) was plotted as a function of the square root of time ($min.^{1/2}$), of which the slope of the curve represents the water absorption coefficient.

Chapter 4. Experimental Results and Analysis

4.1. Compressive strength

Figure 4.1. Compressive strength of 12 test groups, arranged by the classification

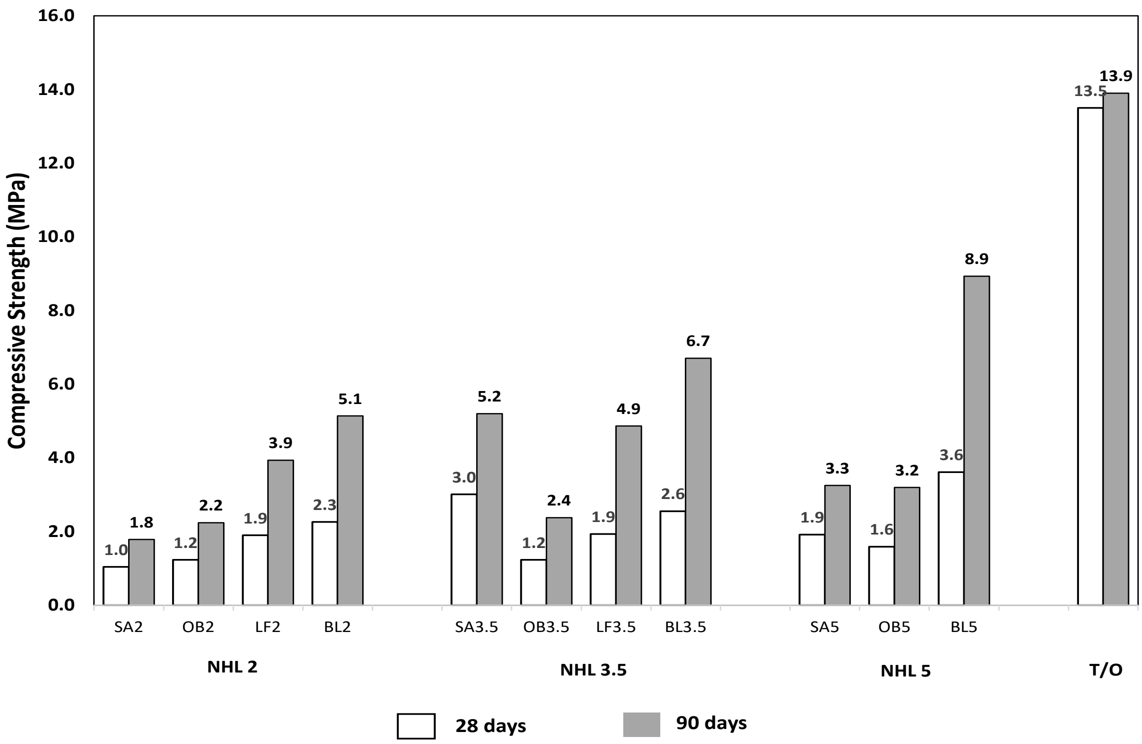


Figure 4.1 illustrates the compressive strength of 11 NHL sample groups and a Type O at 28 days and 90 days. The data for the four NHL brands studied in this thesis were arranged by their classification, NHL 2 on the left, NHL 3.5 at the center, NHL 5 on the right, and Type O at the very end. Data for 28 days (white bar) and 90 days (gray bar) graph were placed out side by side to see the change of strength easily. None of the NHLs meets the 28-day minimum strength specified in EN 459. As a reminder, this was expected, as the research adopted a mix ratio commonly used in conservation practice and not one used for typical EN 459 standard mortars. Each bar represents an average of six specimens, except for the Type O mortar where the bar are an average of three specimens. All 28 day and 90 day data were Q-tested to search for the outliers;

the data were in a close range and no specimens were eliminated.

The compressive strength data was different from expectation, as showing the strength sequence does not follow the order of classification. As an example, NHL 2 and 3.5 of Otterbein had almost identical strength at 28 days, with both at 1.2 MPa. Their 90 days strength was also close, with only an 8% difference between Otterbein NHL 2 (2.2 MPa) and NHL 3.5 (2.4 MPa). A similar pattern was observed in the 28-day strength of Lafarge NHL 2 and 3.5, where both mortars recorded 1.9 MPa. However, at 90 days, these two groups developed some difference in strength, with Lafarge NHL 3.5 being 20% stronger than Lafarge NHL 2. Another unusual result was that NHL 3.5 from St. Astier was significantly stronger than St. Astier NHL 5 mortar at both 28 days and 90 days. St. Astier NHL 3.5 mortars were recorded at 3.2 MPa at 28 days and 5.2 MPa at 90 days, 57% stronger than St. Astier NHL 5 tested at the same days. In summary, three out of the four brands show that strengths does not necessarily increase with increasing strength class; NHL 2 and NHL 3.5 of Otterbein and Lafarge were equal, and for the St. Astier, NHL 3.5 was significantly stronger than NHL 5.

Figure 4.2: Percentage increase in strength. (Unit: MPa)

Brand	Class	28 day	90 day	Strength gained (%)
SA	SA2	1.0	1.8	71%
	SA3.5	3.0	5.2	73%
	SA5	1.9	3.3	70%
OB	OB2	1.2	2.2	82%
	OB3.5	1.2	2.4	93%
	OB5	1.6	3.2	99%
LF	LF2	1.9	3.9	107%
	LF3.5	1.9	4.9	152%
BL	BL2	2.3	5.1	127%
	BL3.5	2.6	6.7	163%
	BL5	3.6	8.9	147%
Type-O		13.5	13.9	3%

As Figure 4.2 shows numerically, Otterbein, Lafarge, and Biolime mortars show considerable variation in strength gain. Only St. Astier mortars gained strength consistently throughout the three classes. There are significant differences between different NHL brands as well. For example, all Biolime mortars showed consistently and more than 120% strength increase, while all St. Astier mortars gained about 70%. Type O mortars showed only 3% strength increase between 28 days and 90 days, suggesting that curing environment designed for the NHL mortars was not appropriate for them.

Figure 4.3. Otterbein mortar: comparison with Figueiredo's study

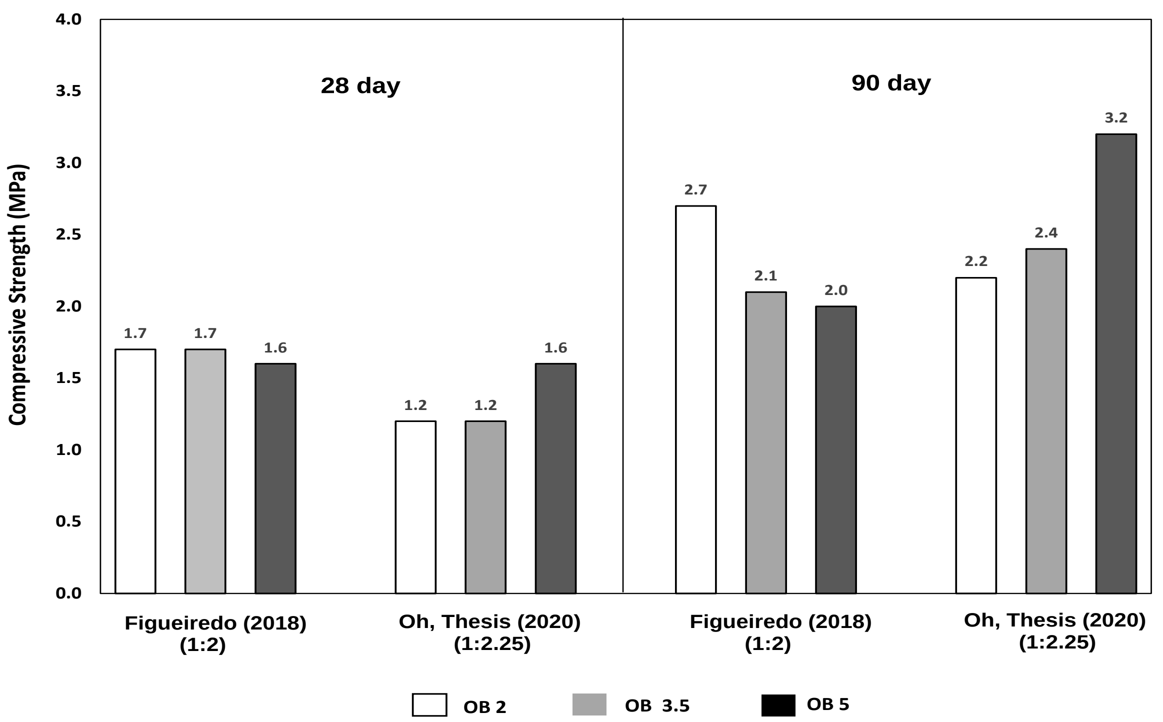


Figure 4.3 compares the compressive strength of Otterbein mortars measured from this research and by Figueiredo in 2018. Similar patterns have been reported by other researchers as well. In his 2018 research, Figueiredo showed that Otterbein NHL 2 and 3.5 had the same strength at 28 days, which is the pattern also found in this thesis.[73] Interestingly, the data sets show a big difference at 90 days, when

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[73] Figueiredo, Cristiano. "Properties and Performance of Lime Mortars for Conservation".

Figueiredo's data reports that the Otterbein NHL 2 has become stronger than NHL 3.5 and even NHL 5. Here, Otterbein NHL 5 turned out to be the weakest mortars among the three classes. The Otterbein mortar studied in this thesis showed, however, that the strength sequence was normal at 90 days, with Otterbein NHL 3.5 being slightly stronger than NHL 2. It is important to note that Figueiredo used a 1: 2 binder-sand ratio for the mixes, which was different from this thesis. Direct comparison of the strength value is not the intention, and the goal is to use it as a general reference to see that the patterns of compressive strength can be different from what is expected from the classifications.

Figure 4.4: Comparison of St. Astier 28-day data. (Figueiredo, Oh, and St. Astier technical data)

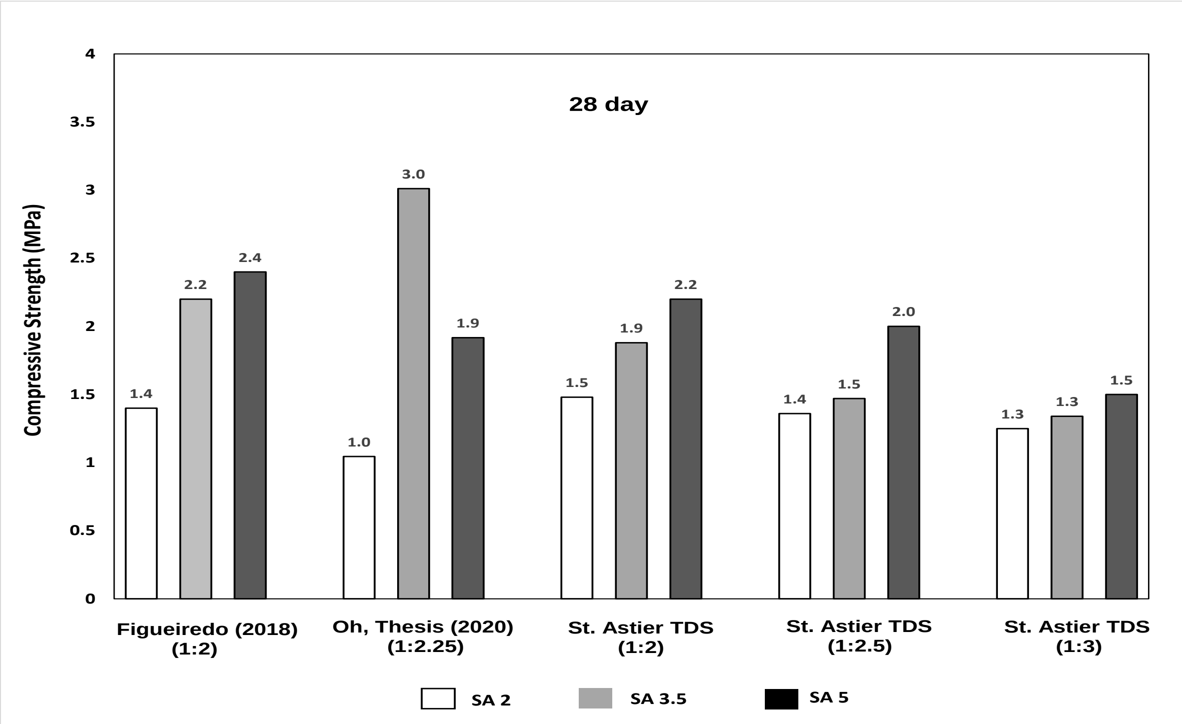
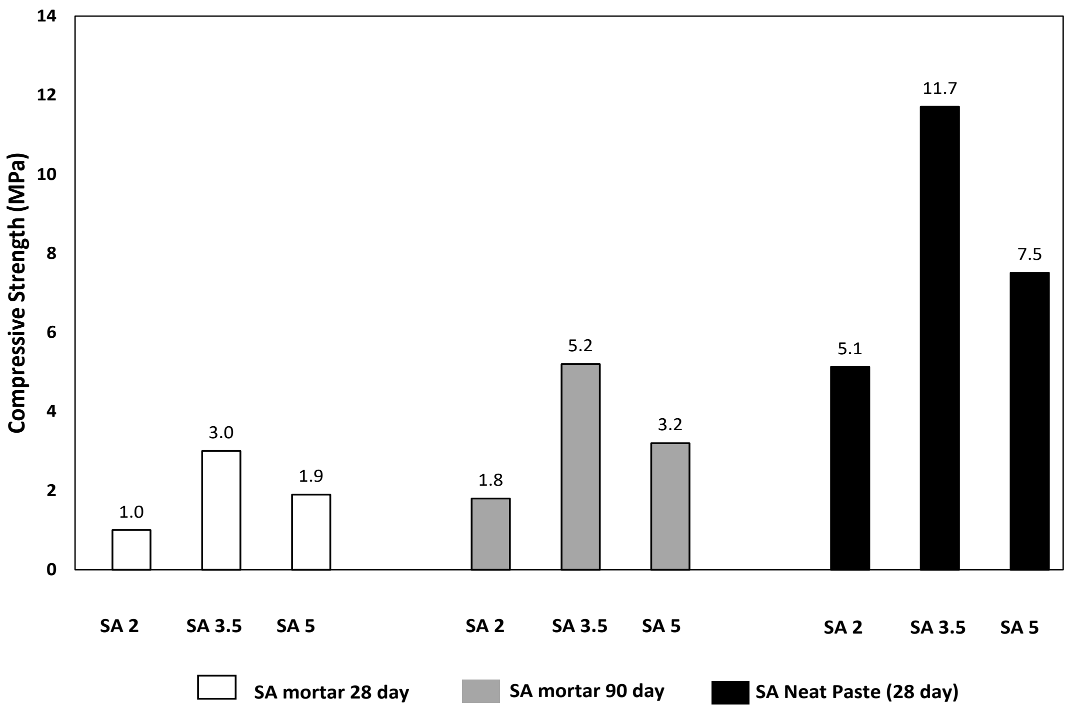


Figure 4.4 compares the compressive strength data of St. Astier mortars with Figueiredo's 2018 research and the technical data sheet (TDS) from St. Astier. As mentioned above, St. Astier NHL 3.5 mortar showed substantially high compressive

strength than NHL 5 mortar, and this interesting result seemed worthy of further investigation. Fortunately, St. Astier company website (http://www.stastier.co.uk/) provides 28-day compressive strength of volumetric 1: 2, 1: 2.5, and 1: 3 mixes, in addition to the EN 459 standard data. St. Astier is the only manufacturer who provides laboratory data based on commonly used mix ratio, which proved to be very useful for the comparative evaluation. Figure 4.4 indicates that the compressive strength of St. Astier NHL 3.5 from this thesis is clearly out of normal range compared to the four data sets other references.[74] The Schork et al.'s 2012 research also reported that the St. Astier NHL 3.5 and NHL 5 mortars had almost identical strength after five months of curing, with 4.15 MPa for NHL 3.5 and 4.20 for NHL 5.[75]

Figure 4.5. Comparison of St. Astier Data (28 day vs 90 day vs neat paste)



74 Figueiredo, Cristiano. "Properties and Performance of Lime Mortars for Conservation"; Schork et al. "Comparative Laboratory Evaluation of Conservation Mortars"

75 Schork et al. "Comparative Laboratory Evaluation of Conservation Mortars"

Figure 4.5 presents a comparison of St. Astier mortars and St. Astier neat paste cubes. There was a question whether the St. Astier data was a result of other factors, such as sand or water content, and not a representation of binder characteristics. To eliminate the other variables and truly see the relationship between strength and the St. Astier binders, three neat paste specimens made of only binder and water were prepared for each of St. Astier NHL 2, 3.5, and 5. Neat paste specimens were made at the same water-binder ratio (0.39) and tested at 28 days of curing. The result was quite interesting, as the data from the neat paste specimens showed a very clear resemblance to the pattern of data from the mortar specimens. This indicates that the mechanical behavior of St. Astier mortars was a result of the binder properties, and not the mix design.

Figure 4.6. NHL mortar compressive strength, arranged by brand

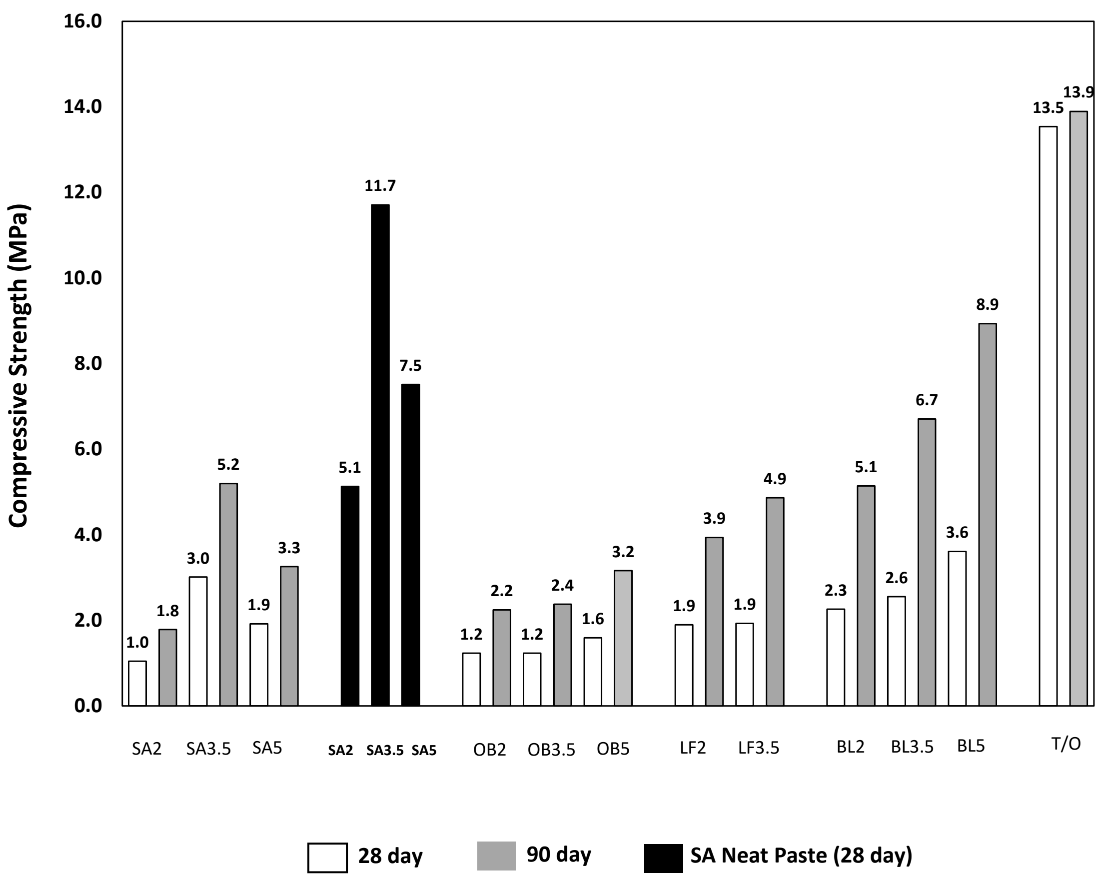


Figure 4.6 displays all compressive strength data by manufacturer. As can be seen on the right. Biolime mortars showed substantially higher compressive strength than the other brands. The NHL 5 mortar from Biolime was the strongest NHL mortar and reached 8.9 MPa at 90 days. Biolime NHL 2 mortars have compressive strength of 5.1 MPa at 90 days, which is almost 60% more stronger than NHL 5 mortars from St. Astier and Otterbein. Biolime NHL 2 is the fourth strongest mortars of the NHLs and its compressive strength is only surpassed by Biolime NHL 3.5, Biolime NHL 5, and St. Astier 3.5. In fact, Biolime NHL 5 mortar is almost twice stronger than the five month compressive strength of St. Astier NHL 5 mortars reported by Schork et al in 2012, which used the same 1 : 2.25 mix ratio.[76] Given that all specimens were cured in the same condition, unusually high strength of Biolime mortars should be a subject of further investigation. It could be yet another representation of varying degree of mechanical properties caused by the inherent variability of limestones with different origins. That being, it is important that none of the NHL mortars reached the strength of Type O mortar specimens, which suggests that despite the variability of mechanical behavior, NHL mortars have medium to low compressive strength in general.

[76] Schork et al. “Comparative Laboratory Evaluation of Conservation Mortars”

4.2. Water vapor transmission

Water vapor transmission testing (WVT) was undertaken to understand the permeability of different NHL mortars. Testing began after the 45 days of curing and continued for 30 days with daily measurements. Water vapor transmission rate is the mass of water vapor passing through a specific area in a measured time and it indicates the mortar's ability to allow moisture to diffuse through its pores. Understanding the permeability of mortar is critical to assessing the performance of conservation mortars.[77]

Figure 4.7. WVT rate of NHL mortars, arranged by brand/binder type

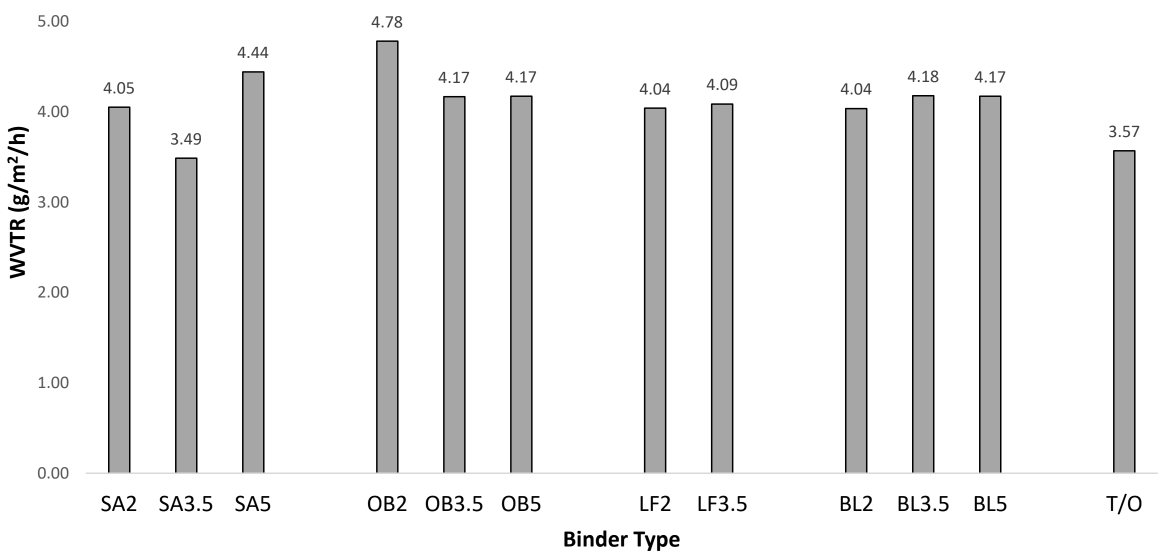


Figure 4.7 illustrates the surprisingly similar WVT rates of NHL mortars and the Type O mortar, measured for 30 days period, between 45 days and 75 days of curing. The graphs show that all NHL mortars have moderately high WVT rate, with most of them were narrowly ranged between 4.04 to 4.44 (g/m^2/h). NHL 3.5 from St. Astier and

[77] Schork et al. "Comparative Laboratory Evaluation of Conservation Mortars"; Weiss, Norman and Judith Jacob "Laboratory Measurement of Water Vapor Transmission Rates of Masonry Mortars and Paints", 1989.,

NHL 2 from Otterbein falls slightly outside the normal range, but only have a 15% difference versus the average. Overall, the testing showed that WVT rate of each mortar was independent of class or brands and that there was no linear correlation with strength property.

These test results turned out to be lower than data reported for previous laboratory-based research. For example, a 2005 study by Atkinson-Noland & Associates (ANA) reported average WVT rates of 7.2 ($g/m^2/h$), 5.1 ($g/m^2/h$), and 5.6 ($g/m^2/h$) for St. Astier NHL 2, 3.5, and 5, respectively.[78] One reason for this discrepancy could be the different mix ratio, as ANA's testing used 1 : 3 binder-sand ratio. Higher sand content might have created a more microporous structure, which could explain the higher WVT rate of the ANA's test result. Interestingly, ANA's experiment reported that St. Astier NHL 5 had 10% higher WVT rate than NHL 3.5, which is similar to the thesis experiment.[79] The WVT rate difference was much greater in the thesis experiment, where the NHL 5 had a 28% higher WVT rate than NHL 3.5. ANA's experiment did not provided comparable compressive strength data. One possible hypothesis could be that the raw material for St. Astier NHL 3.5 contains more hydraulic reactive components, which led to the subsequent filling of the micro-pores.[80] The Schorck et al.'s 2012 research provided more comparable data set as the thesis borrowed many of the testing protocol from their study. They used the same 0.75 inch thickness for the disk specimens and a 1 : 2.25 mix ratio. The 2012 article presented similar WVT rate values, 3.40 ($g/m^2/h$) for Type O mortar and 4.33 ($g/m^2/h$), 4.15 ($g/m^2/h$), and

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[78] Atkinson-Noland & Associates, "Water Transport Characteristics of Masonry Restoration Mortars (2004-26)", NCPTT, In Architectural and Engineering, Grants, Materials Conservation, Product Catalog, Reports. 2004

[79] Ibid.

[80] Isabert, A. et al. "Pore-related Properties of Natural Hydraulic Lime Mortars: An Experimental Study" Materials and Structures (2016) 49:2767–2780

3.81(g/m^2/h) for St Astier NHL 2, 3.5, and 5.

Otterbein 2 had the highest individual value of 4.78 (g/m^2/h). Lafarge and Biolime mortars showed little or no difference in WVT rate by class. Type O mortar had a 14% lower value than the average WVT rate of NHL mortars. To summarize, the WVT rate of NHL mortars does not vary appreciably between brands and classes.

4.3. Water absorption by capillary uptake

Figure 4.8: Water absorption rate, arranged by manufacturer/binder type

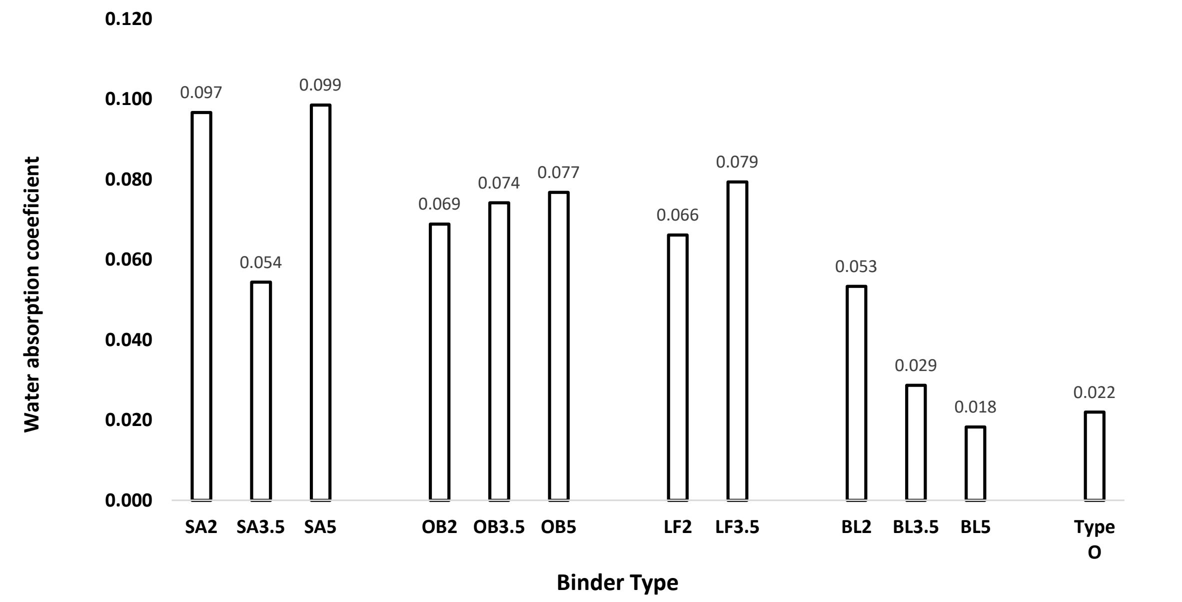

Figure 4.8 shows the water absorption rate of 11 NHL mortars, arranged by manufacturer. Characterization of porosity by the absorption of liquid water is another important parameter related to the physical compatibility between mortars and masonry. Water absorption rate indicates the ability of the mortar to promote movement of moisture from the masonry unit. Water absorption rate was measured at 90 days of curing and the data were recorded individually. The average of 3 cube specimens for each of the 12 test groups were then recorded.

In general, NHL mortars seem to have a high water absorption rate, significantly higher than that of Type O mortar. In most of the NHL mortars, water reached the top of the samples within 4 hours. However, In case of the Type O and Biolime NHL 3.5, and 5, it took more than 8 hours for water to reach the top. This result is different from other experimental research. For example, Schork et al. reported that the water absorption rate of Type O mortar was quite high, close to that of the NHL mortars and hydrated lime mortars.[81]

No obvious correlation was found from the water absorption rate and the composition of NHL mortar. As an example, the one that recorded the highest water absorption rate was St. Astier NHL 5. It was even slightly higher than St. Astier 2, which had much higher water-binder ratio (W/B) and more sand by weight; W/B of St. Astier NHL 5 was 0.89, while the St. Astier 2 was 1.16.[82] Similar data was reported on Otterbein mortars too, and both Otterbein NHL 3.5 and 5 mortars showed slightly higher water absorption rate than Otterbein NHL 2.

Notably low absorption rates of the three Biolime mortars were also interesting. All three of the Biolime NHL mortars recorded the lowest water absorption coefficient among all NHL samples, and in case of Biolime NHL 5, it was even lower than the Type O mortar (Fig. 4.7).   Biolime NHL 5 mortar was mixed at low W/B ratio (0.76) than the average of NHLs (1.0), but the W/B of Biolime NHL 2 (0.97) and NHL 3.5 (0.95) was not so different from the average. Still, significantly low water absorption rate was found from all three of Biolime NHLs. This unexpected data might indicate that bulk density from technical data sheets are substantially different from the actual density of material.

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[81] Schork et al. “Comparative Laboratory Evaluation of Conservation Mortars”

[82] Water-binder ratio of each NHL mortars are illustrated in chapter 3, figure 3.5.

However, it was difficult to explain the reason behind this varying water absorption rate of NHL mortars only from the presented data. In addition, each individual binder's water absorption rate by time were presented through figure 4.9 to 4.12

Figure 4.9: Water absorption rate of St. Astier mortars cured for 90 days

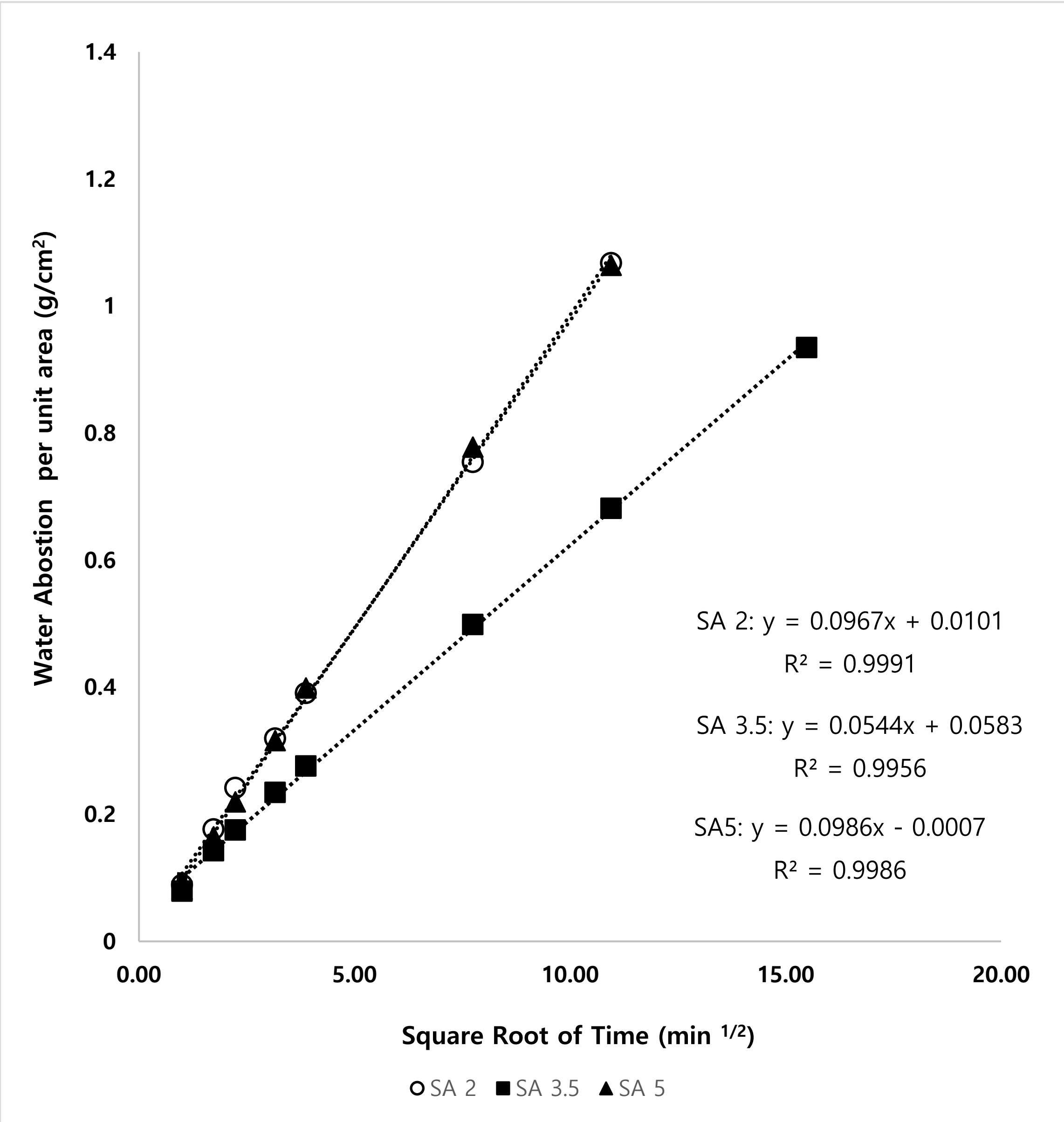


Figure 4.10: Water absorption rate of Otterbein mortars cured for 90 days

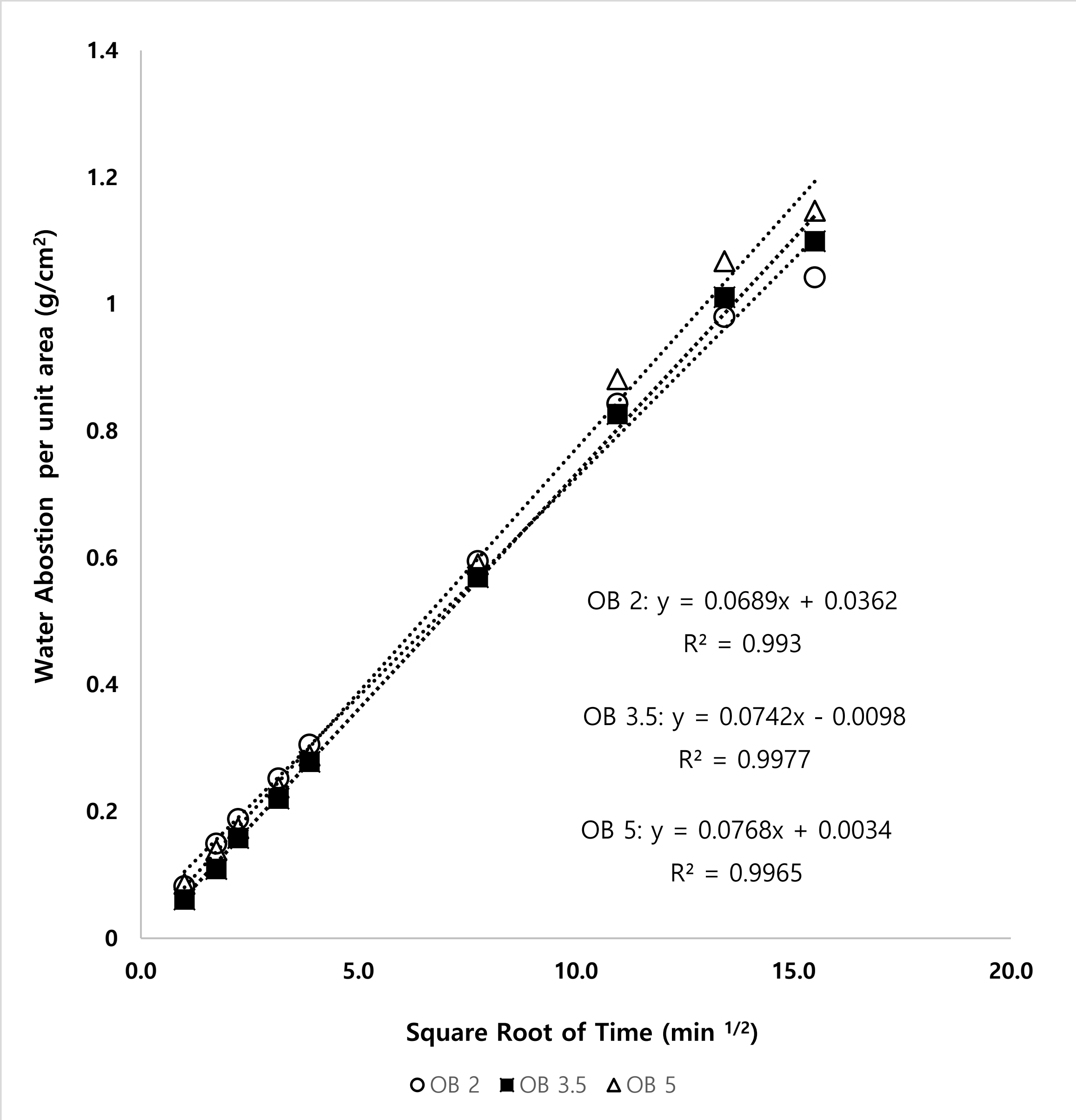


Figure 4.11: Water absorption rate of Lafarge mortars cured for 90 days

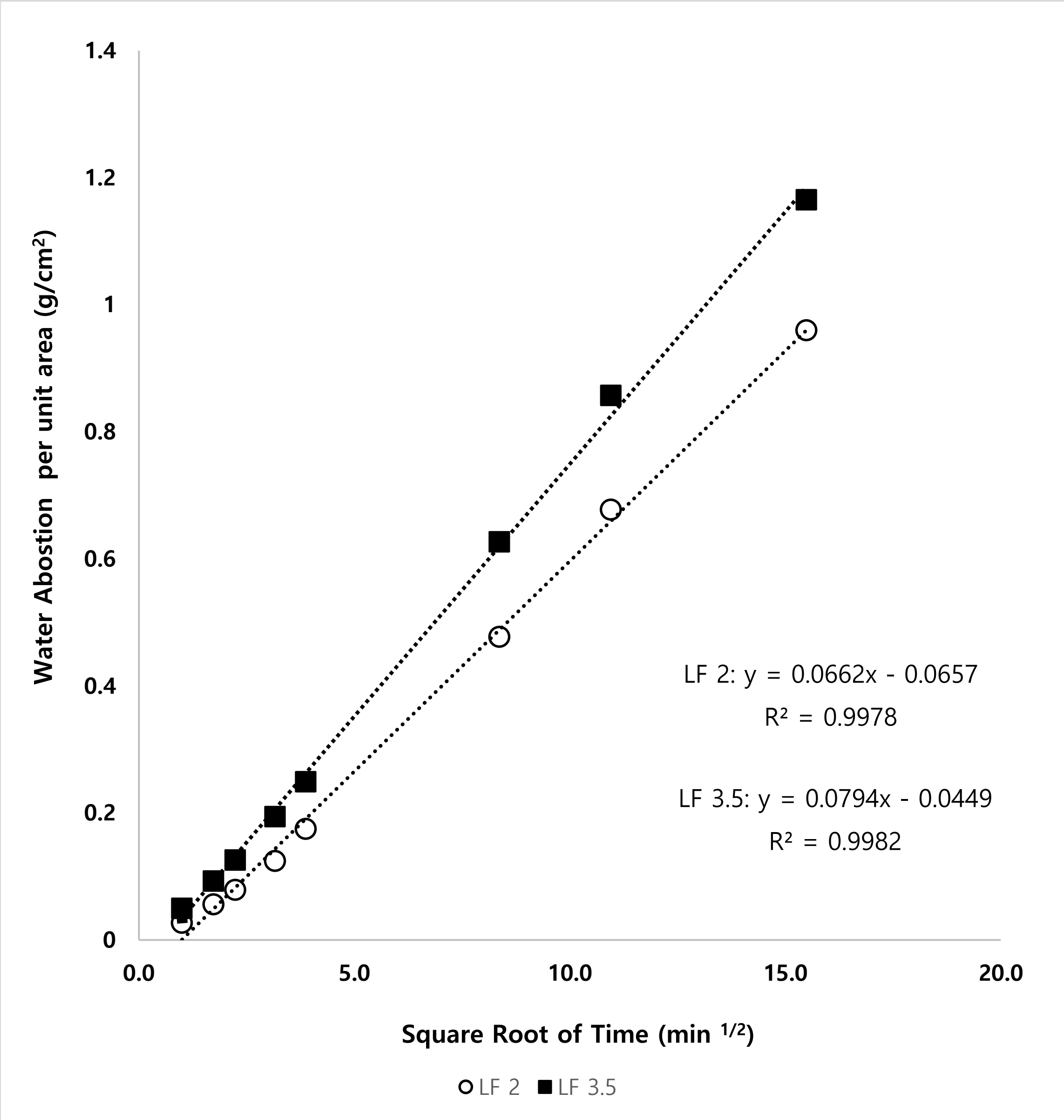
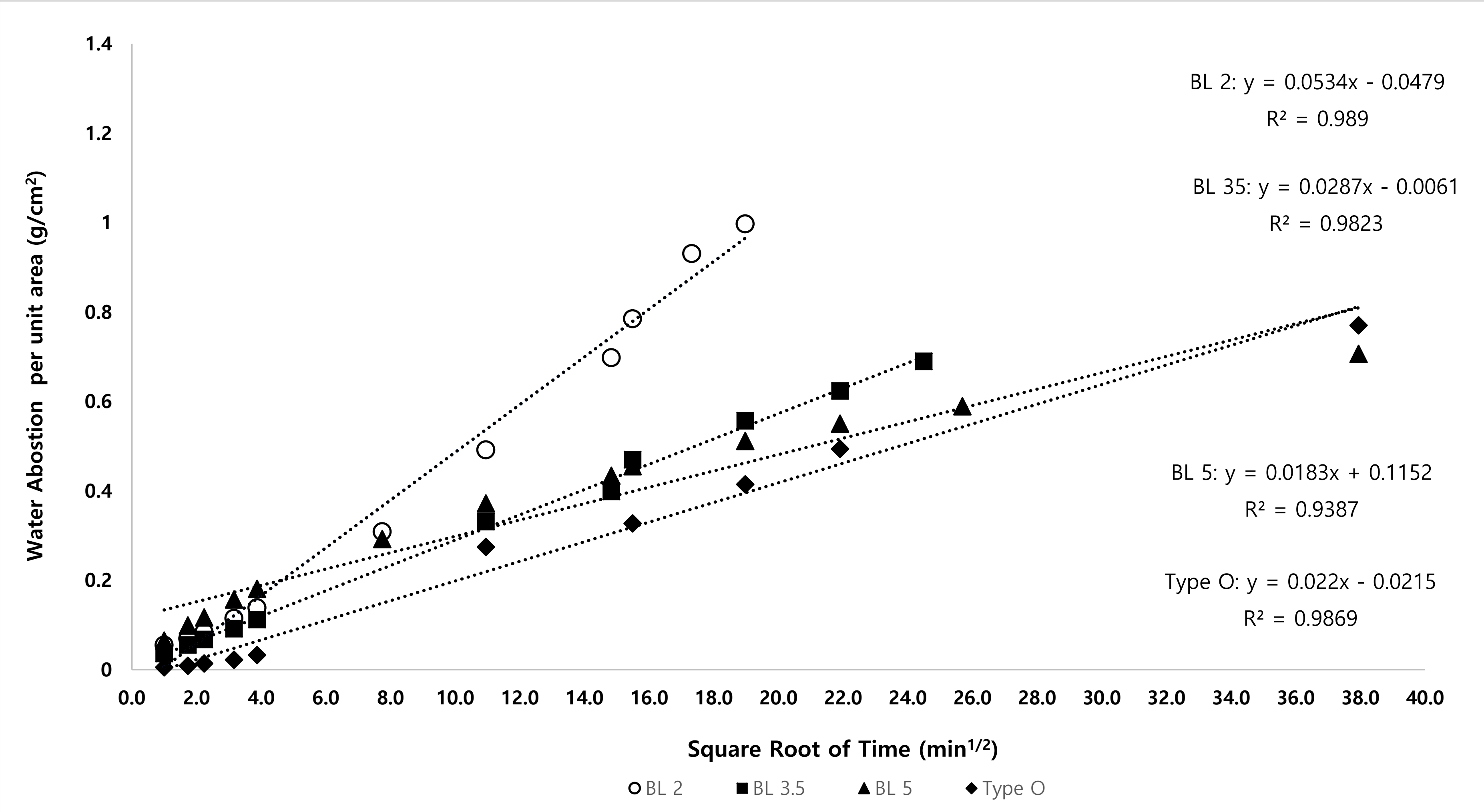


Figure 4.12: Water absorption rate of Biolime and Type O mortars cured for 90 days



Chapter 5. Conclusion and Discussions

5.1. Summary of key findings

The key findings of this research are summarized below:

- The compressive strength of many NHL mortars does not reflect the graded classifications of NHL 2, NHL 3.5, and NHL 5. Some NHL 2 or 3.5 mortars actually have equal or higher strength than the highest class.

- Some NHL mortars of different classes show the same compressive strength. OB 2 and OB 3.5 presented identical strength at 28 days and only an 8% difference at 90 days.

- All NHL mortars gained greater strength between 28 days and 90 days, but the percentage increase shows great variability. The only exception was with the St. Astier mortars, of which the strength increased 70% consistently in all three classes.

- There is a notable difference in compressive strength among the different NHL brands. As one example, Biolime NHL 5's compressive strength is 270% of St. Astier NHL 5 or Otterbein NHL 5 at 90 days, and St. Astier 3.5 is 150% stronger than Otterbein 3.5 at 28 days.

- All NHL mortars with 45 days of curing have a moderately high water vapor transmission rate. The WVT rate of all NHL mortars seems to be independent of brand or class, and the degree of difference is not substantial.

- No clear co-relationship between WVT rate and compressive strength was found.

- In general, although NHL mortars show high water absorption rates, no consistent pattern was found to associate that with the water-binder ratio. St. Astier NHL 5 mortar, which has a relatively low water-binder ratio compared to the nearly all of other mortars, still recorded a very high water absorption rate.

- When compared to Type O mortar made with the same 1 : 2.25 binder-sand ratio, compressive strength of all NHL mortars was lower than that of Type O. All NHL mortars have similar or higher WVT rates, 15% higher than the Type O mortar on average. The water absorption rate of NHL mortars was much higher than that of Type O, except for the Biolime NHL 3.5 and 5.

5.2. Discussion about the finding

The overall approach for this research involved eliminating the variables of mix design except for binder selection, thus creating comparable data for the study of the different binders. This methodology was borrowed from the Schork et al. 2012 research and proved to be vital for comparing a number of NHL binders as well as for creating reproducible data.[83]

Much of the data gathered in this research was surprisingly different from what was expected from the testing standard and from manufacturers' data, raising many questions about the mechanical and physical properties of NHL mortars. Overall, this data seems to indicate that the properties of all NHL mortars are heavily reliant on the mineralogy of the source rock, and so the classification is not a practical tool for predicting mechanical behavior. This can be a serious issue in conservation, as architectural conservators are often required to make assumptions

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[83] Schork et al. "Comparative Laboratory Evaluation of Conservation Mortars"

on mortar performance based on product data sheets. Currently most of the manufacturers' data, with exception of St. Astier, only reports the 28-day compressive strength to prove that their product meets the minimum requirements of EN 459.

The thesis data shows that the NHL 5 from Biolime can be almost three times stronger than NHL 5 from St. Astier or Otterbein prepared in same condition, suggesting that mechanical properties can be very different from one manufacturer to another. Such surprising results were also found for a single manufacturer. For end users, it is obvious to expect strengths to always increase with increasing strength class under the same test conditions. In other words, NHL 5 should always yield the highest strength from any one manufacturer's product line. However, St. Astier NHL 3.5 turns out be 1.5 times stronger than St. Astier NHL 5. This was determined to be the case even when each of the St. Astier binders was tested neat (that is with no aggregate) and the same water-binder ratio. It would be difficult for conservators to predict such an anomaly unless they can test the materials thoroughly before using them. Depending on the type of masonry unit and the function of the mortar, this varying performance of NHL mortars can have a serious impact on “compatibility.”

Some NHL binders from the same manufacturer have very similar compressive strength, which raises a question about the chemical composition of each binder. The fact that Otterbein NHL 2 and 3.5 recorded almost identical compressive strength at both 28 days and 90 days may indicate that they were made from same source material and underwent only minor changes during the manufacturing process. The same question applies to Lafarge NLH 2 and 3.5

mortars, where we can see identical strength at 28 days and only about a 20% strength difference at 90 days. As noted earlier, calcination temperature and duration can have influence on the mechanical properties of an NHL, but little is known regarding the specific manufacturing process of each brand.[84]   These questions, of course, cannot be answered from this thesis alone and require additional analysis on chemical composition of each binder, which is an interesting subject for future research.

Overall, the compressive strength data reported in this thesis supports the observation of other laboratory-based researches, who have stated that NHL mortars can be "unpredictable" in term of compressive strength.[85] Although a certain degree of variability is expected for being "natural", it is concerning that this characteristic is overlooked in most of the manufacturers' data, even though meeting the EN 459 standard is emphasized. This can be misleading for end users working in architectural conservation, because high strength is not necessarily a favorable attribute for the conservation mortar and should not be the primary criterion for the "compatibility." As discussed in Chapter 1 and 2, assessment of "compatibility" entails an examination of the present condition of masonry units, and mortar properties are only one aspect of the picture. In the context of masonry conservation, knowing that NHL mortars can have wide range of variability in mechanical and physical property is much more relevant than knowing that the

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[84] Elsen, Jan & Van Balen, Koenraad & Mertens, Gilles. Hydraulicity in Historic Lime Mortars: A Review, RILEM Book series, 2011. doi:10.1007/978-94-007-4635-0_10. Eckel, Edwin C., Cements, limes, and plasters; their materials, manufacture, and properties.

[85] Henry, Alison et. al. "Hydraulic Lime Production Coming Full Circle?"; Figueiredo, Cristiano. "Properties and Performance of Lime Mortars for Conservation"; Veiga, M. et al. "Lime-based Mortars: Viability for Use as Substitution Renders in Historical Buildings."

“standard mortar” as per EN 459 exceeds a certain minimum strength.

Regarding the WVT testing, the pattern of data was somewhat confusing, and it was difficult to establish a correlation between specific variable and the vapor permeability of NHLs. Initially, the data was analyzed to see if there was a potential correlation between water-binder ratio and vapor permeability. On the one hand, Otterbein NHL 2 mortar, which has the highest water-binder ratio among the NHLs, did record highest WVT rate, suggesting a positive correlation between these two variables. However, most of the other NHL mortars presented moderately high WVT rate regardless of their water-binder ratio. For example, Biolime NHL 5 has substantially low water-binder ratio (0.76) than the average of NHL test groups (1.0), but still shows a moderately high WVT rate, even higher than the Biolime NHL 2 or Lafarge NHL 2. Similarly, samples made with St. Astier NHL 5 has relatively low water-binder ratio (0.89), but still recorded the second highest WVT rate within all NHL test groups.

The WVT rate data does not reveal any obvious correlation with compressive strength either. In case of St. Astier NHL 3.5, there was moderately high strength, but the lowest WVT rate, even lower than for the Type O mortars. On the other hand, some stronger mortars like Biolime NHL 5 and Lafarge NHL 3.5 actually show slightly higher WVT rates than the weaker St. Astier NHL 2. These results could be related to a different microstructure of each mortar based on varying degrees of hydraulic components in the binder. However, it could also be evidence that the curing protocol failed to provide uniform a environment for hydration. In conclusion, the WVT experiment yielded data for an expected range of WVT rate of NHL mortars, but did not identify the variables which affected the permeability of specific mortars. Further research and testing seem necessary to fully understand the vapor permeability of NHLs.

As with WVT, water absorption testing was carried out with the expectation that the rates of NHLs would be related to the relative proportions of binder, water, and sand. This expectation proved to be wrong. On one hand, the mortar with the lowest water absorption rate (Biolime NHL 5) did have the lowest water-binder ratio. The mortar with the highest water absorption rate (St. Astier NHL 5), however, has the second lowest water-binder ratio within all NHL test groups. The mortar with the highest water-binder ratio (Otterbein NHL 2) had a 30% lower water absorption coefficient than the St. Astier NHL 5. This confusing pattern could be the result of some unique characteristics of the binders or might only represent deficiencies in the preparation of laboratory specimens. It was unfortunate that the absorption experiment was not a conclusive evaluation of this parameter, but it is certainly on opportunity for future research.

Finally, having Type O mortar as a comparable reference for NHL mortars may be informative for predicting the general performance of NHL mortars in building conservation. Type O mortar has been used for the repair of historic masonry in North America, due to the favorable attributes associated with the relatively high content of hydrated lime.[86] Although NHL mortars can have great variability in their mechanical and physical properties, none of them reached the 28-day compressive strength of Type O, and 10 out of 11 NHL mortars have a higher water absorption rate as compared to Type O. WVT rates of Type O and NHL mortars seemed to be

[86] Mack C. Robert, Speweik, John & Anne E. Girmmer. National Park Service. “Preservation Brief 2: Repointing Mortar Joints in Historic Masonry Buildings”, National Park Service, 1998. Retrieved, May, 2020.

relatively similar, but the NHL mortars have somewhat higher WVT rate on average. The test results have shown that there is a certain disconnect between the conservator's expectations and the material performance of the NHLs. This can raise questions regarding the suitability of NHL mortars for use of many historic buildings. Still, some perspective is offered by the comparison with Type O mortar. If a typical Type O mix is considered to be a suitable repair material, then the more favorable properties of NHL mixes would suggest that these could be comparatively appropriate at the very least.

Chapter 6. Suggestions for Future Research

This research has revealed certain limitations and uncertainties, which can certainly be better and more thoroughly addressed in the future. Some of ideas and recommendations are presented here.

- The bulk density of the NHL binders should be measured directly, to improve the quality of mixes and lessen the variables of consistency. One of the limitations of this thesis is that the author used manufacturers' reported densities for determining the amount of binder, sand, and water. It is possible that the specimens do not represent precisely the same 1: 2.25 mix ratio due to discrepancies between actual density and the product data. The standard for determining the bulk density of an NHL binder is described in EN 459-2: 2010.[87]

- A strength growth curve showing 28 day, 90 day, 6 month, and 12 months would be helpful for a more complete understanding of the long-term mechanical properties of NHL mortars. As seen in Chapter 4, the percentage increase in strength shows great differences within each binder group and from group to group. Compressive strength data in this thesis only presents the changes for 28 days to 90 days. It is important to see how this parameter changes over an extended period of time.

- Determining the chemical composition of each NHL could provide an explanation of some of unpredictable characteristics of these binders. St. Astier binders used in this thesis, for example, showed some very unexpected data, and the testing of neat paste made it very likely that this result was derived from binder chemistry rather

[87] CEN, EN 459-2:2010 - Building lime. Test methods.,

than from mix design. It would be interesting to see how the specific composition of hydraulic components in the St. Astier binders affected the final properties of the mortars. The same suggestion applies for the Otterbein mortars, where we see virtually the same compressive strength in its NHL 2 and NHL 3.5. Both X-ray diffraction analysis (with Rietveld refinement) and atomic absorption spectroscopy have previously been used by researchers for quantifying the chemistry of binders.[88]

- Expanding the neat paste testing can provide important data for the further study of mortar strength. It is recommended to make neat paste cubes for Biolime and Otterbein, as they gave data that is particularly interesting.

- Curing protocol can be refined with a method to visually assess the carbonation behavior of mortars. The compressive strength data showed that Type O mortar gained only 3% of strength between 28 days and 90 days, indicating that the curing environment used for the NHLs was insufficient for the Type O. In the future, an extra specimen for each test group can be sliced before the testing, to examine the depth of carbonation and evaluate the effectiveness of the curing condition. This methodology was used in the Schork et al. 2012 research to prove the efficacy of the curing protocol.[89]

- Some NHL mortars have yielded unusual data regarding the water absorption rate and WVT rate. Petrographic examination should be conducted to characterize the pore structure of NHL mortars and to determine whether the data is a direct result of

[88] Marques et al. "Study of rehabilitation mortars: Construction of a knowledge correlation matrix." Cement and Concrete Research, 36(10), pp.1894–1902; Gleize at al. "Characterization of historical mortars from Santa Catarina (Brazil)." Cement and Concrete Composite, Vol.31, May 2009, Pages 342-346

[89] Schork et al. "Comparative Laboratory Evaluation of Conservation Mortars"

binder properties, or some issues in sample preparation.

- Aggregate always has a significant influence on mortar performance. Detailed analysis of the bulk density, particle shape, and size distribution would be helpful for establishing a more accurate evaluation of NHL mortars, particularly with respect to microstructure.

- Compressive strength, WVT, and water absorption rate are important parameters for evaluating the “compatibility” between mortar and masonry unit, but this list of parameters and criteria is certainly not complete. There are other physical and mechanical properties that affects the mortar-masonry interaction, including elastic modulus, flexural strength, thermal dilation, and pull-off strength, for example. Establishing the range of these properties through experimentation will be a challenging task, but is nonetheless important for judging the performance of NHL mortars for the repair of different masonry types.

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Appendix A: Experiment Raw Data

Compressive strength raw data: 28-day

Binder	ID	Load (lbs)	psi	Mpa	date made	date tested
Saint Astier 2	S-28-SA2-1	576	144	0.99	12/14/2019	01/10/2020
	S-28-SA2-2	642	160.5	1.11	12/14/2019	01/10/2020
	S-28-SA2-3	605	151.25	1.04	12/14/2019	01/10/2020
	S-28-SA2-4	626	156.5	1.08	12/14/2019	01/10/2020
	S-28-SA2-5	534	133.5	0.92	12/14/2019	01/10/2020
	S-28-SA2-6	652	163	1.12	12/14/2019	01/10/2020
Saint Astier 3.5	S-28-SA3.5-1	1800	450	3.10	12/14/2019	01/10/2020
	S-28-SA3.5-2	1699	424.75	2.93	12/14/2019	01/10/2020
	S-28-SA3.5-3	1750	437.5	3.02	12/14/2019	01/10/2020
	S-28-SA3.5-4	1627	406.75	2.80	12/14/2019	01/10/2020
	S-28-SA3.5-5	1807	451.75	3.11	12/14/2019	01/10/2020
	S-28-SA3.5-6	1798	449.5	3.10	12/14/2019	01/10/2020
Saint Astier 5	S-28-SA5-1	1130	282.5	1.95	12/14/2019	01/10/2020
	S-28-SA5-2	1096	274	1.89	12/14/2019	01/10/2020
	S-28-SA5-3	1106	276.5	1.91	12/14/2019	01/10/2020
	S-28-SA5-4	1165	291.25	2.01	12/14/2019	01/10/2020
	S-28-SA5-5	1051	262.75	1.81	12/14/2019	01/10/2020
	S-28-SA5-6	1127	281.75	1.94	12/14/2019	01/10/2020
Otterbein 2	S-28-OB2-1	705	176.25	1.22	12/17/2019	01/13/2020
	S-28-OB2-2	682	170.5	1.18	12/17/2019	01/13/2020
	S-28-OB2-3	664	166	1.14	12/17/2019	01/13/2020
	S-28-OB2-4	750	187.5	1.29	12/17/2019	01/13/2020
	S-28-OB2-5	719	179.75	1.24	12/17/2019	01/13/2020
	S-28-OB2-6	766	191.5	1.32	12/17/2019	01/13/2020
Otterbein 3.5	S-28-OB3.5-1	734	183.5	1.27	12/17/2019	01/13/2020
	S-28-OB3.5-2	676	169	1.17	12/17/2019	01/13/2020
	S-28-OB3.5-3	689	172.25	1.19	12/17/2019	01/13/2020
	S-28-OB3.5-4	723	180.75	1.25	12/17/2019	01/13/2020
	S-28-OB3.5-5	745	186.25	1.28	12/17/2019	01/13/2020
	S-28-OB3.5-6	729	182.25	1.26	12/17/2019	01/13/2020

Otterbein 5	S-28-OB5-1	963	240.75	1.66	12/17/2019	01/13/2020
	S-28-OB5-2	907	226.75	1.56	12/17/2019	01/13/2020
	S-28-OB5-3	924	231	1.59	12/17/2019	01/13/2020
	S-28-OB5-4	940	235	1.62	12/17/2019	01/13/2020
	S-28-OB5-5	890	222.5	1.53	12/17/2019	01/13/2020
	S-28-OB5-6	909	227.25	1.57	12/17/2019	01/13/2020
Lafarge 2	S-28-LF2-1	1127	281.75	1.94	12-20-2019	1/16/2020
	S-28-LF2-2	1121	280.25	1.93	12-20-2019	1/16/2020
	S-28-LF2-3	1140	285	1.97	12-20-2019	1/16/2020
	S-28-LF2-4	1103	275.75	1.90	12-20-2019	1/16/2020
	S-28-LF2-5	1079	269.75	1.86	12-20-2019	1/16/2020
	S-28-LF2-6	1038	259.5	1.79	12-20-2019	1/16/2020
Lafarge 3.5	S-28-LF3.5-1	1111	277.75	1.92	12-20-2019	1/16/2020
	S-28-LF3.5-2	1155	288.75	1.99	12-20-2019	1/16/2020
	S-28-LF3.5-3	1134	283.5	1.95	12-20-2019	1/16/2020
	S-28-LF3.5-4	1096	274	1.89	12-20-2019	1/16/2020
	S-28-LF3.5-5	1107	276.75	1.91	12-20-2019	1/16/2020
	S-28-LF3.5-6	1119	279.75	1.93	12-20-2019	1/16/2020
Biolime 2	S-28-BA2-1	1308	327	2.25	12-24-2019	1/20/2020
	S-28-BA2-2	1336	334	2.30	12-24-2019	1/20/2020
	S-28-BA2-3	1330	332.5	2.29	12-24-2019	1/20/2020
	S-28-BA2-4	1320	330	2.28	12-24-2019	1/20/2020
	S-28-BA2-5	1327	331.75	2.29	12-24-2019	1/20/2020
	S-28-BA2-6	1247	311.75	2.15	12-24-2019	1/20/2020
Biolime 3.5	S-28-BA3.5-1	1442	360.5	2.49	12-24-2019	1/20/2020
	S-28-BA3.5-2	1450	362.5	2.50	12-24-2019	1/20/2020
	S-28-BA3.5-3	1461	365.25	2.52	12-24-2019	1/20/2020
	S-28-BA3.5-4	1525	381.25	2.63	12-24-2019	1/20/2020
	S-28-BA3.5-5	1526	381.5	2.63	12-24-2019	1/20/2020
	S-28-BA3.5-6	1487	371.75	2.56	12-24-2019	1/20/2020
Biolime 5	S-28-BA5-1	2065	516.25	3.56	12-24-2019	1/20/2020
	S-28-BA5-2	2148	537	3.70	12-24-2019	1/20/2020
	S-28-BA5-3	2175	543.75	3.75	12-24-2019	1/20/2020
	S-28-BA5-4	2094	523.5	3.61	12-24-2019	1/20/2020

	S-28-BA5-5	2071	517.75	3.57	12-24-2019	1/20/2020
	S-28-BA5-6	2016	504	3.47	12-24-2019	1/20/2020
Type O (1:2.5:7.88)	S-28-Type O	7,840	1,960	13.51	12-23-2019	2/25/2020
	S-28-Type O	8,040	2,010	13.86	12-23-2019	2/25/2020
	S-28-Type O	7,680	1,920	13.24	12-23-2019	2/25/2020
SA 2 Neat Paste	SA2-28-N1	3,300	825	5.69	01-29-2020	2/25/2020
	SA2-28-N2	2,760	690	4.76	01-29-2020	2/25/2020
	SA2-28-N3	2,870	718	4.95	01-29-2020	2/25/2020
SA 3.5 Neat Paste	SA3.5-28-N1	6,790	1,698	11.70	01-29-2020	2/25/2020
	SA3.5-28-N2	6,910	1,728	11.91	01-29-2020	2/25/2020
	SA3.5-28-N3	6,680	1,670	11.51	01-29-2020	2/25/2020
SA 5 Neat Paste	SA5-28-N1	4,090	1,023	7.05	01-29-2020	2/25/2020
	SA5-28-N2	4,350	1,088	7.50	01-29-2020	2/25/2020
	SA5-28-N3	4,630	1,158	7.98	01-29-2020	2/25/2020

Compressive strength raw data: 90-day

Binder	ID	Load (lbs)	psi	Mpa	date made	date tested
Saint Astier 2	S-90-SA2-1	1121	280.25	1.93	11/19/2019	02/17/2020
	S-90-SA2-2	828	207	1.43	11/19/2019	02/17/2020
	S-90-SA2-3	1077	269.25	1.86	11/19/2019	02/17/2020
	S-90-SA2-4	1115	278.75	1.92	11/19/2019	02/17/2020
	S-90-SA2-5	1062	265.5	1.83	11/19/2019	02/17/2020
	S-90-SA2-6	1010	252.5	1.74	11/19/2019	02/17/2020
Saint Astier 3.5	S-90-SA3.5-1	2948	737	5.08	11/19/2019	02/17/2020
	S-90-SA3.5-2	3021	755.25	5.21	11/19/2019	02/17/2020
	S-90-SA3.5-3	3128	782	5.39	11/19/2019	02/17/2020
	S-90-SA3.5-4	3087	771.75	5.32	11/19/2019	02/17/2020
	S-90-SA3.5-5	3012	753	5.19	11/19/2019	02/17/2020
	S-90-SA3.5-6	2897	724.25	4.99	11/19/2019	02/17/2020
Saint Astier 5	S-90-SA5-1	1957	489.25	3.37	11/19/2019	02/17/2020
	S-90-SA5-2	2009	502.25	3.46	11/19/2019	02/17/2020
	S-90-SA5-3	1687	421.75	2.91	11/19/2019	02/17/2020
	S-90-SA5-4	1897	474.25	3.27	11/19/2019	02/17/2020
	S-90-SA5-5	1884	471	3.25	11/19/2019	02/17/2020
	S-90-SA5-6	1892	473	3.26	11/19/2019	02/17/2020
Otterbein 2	S-90-OB2-1	1430	357.5	2.46	11/22/2019	2/20/2020
	S-90-OB2-2	1551	387.75	2.67	11/22/2019	2/20/2020
	S-90-OB2-3	1448	362	2.50	11/22/2019	2/20/2020
	S-90-OB2-4	1259	314.75	2.17	11/22/2019	2/20/2020
	S-90-OB2-5	943	235.75	1.63	11/22/2019	2/20/2020
	S-90-OB2-6	1174	293.5	2.02	11/22/2019	2/20/2020
Otterbein 3.5	S-90-OB3.5-1	1351	337.75	2.33	11/22/2019	2/20/2020
	S-90-OB3.5-2	1404	351	2.42	11/22/2019	2/20/2020
	S-90-OB3.5-3	1412	353	2.43	11/22/2019	2/20/2020
	S-90-OB3.5-4	1354	338.5	2.33	11/22/2019	2/20/2020
	S-90-OB3.5-5	1384	346	2.39	11/22/2019	2/20/2020
	S-90-OB3.5-6	1374	343.5	2.37	11/22/2019	2/20/2020
Otterbein 5	S-90-OB5-1	1815	453.75	3.13	11/22/2019	2/20/2020
	S-90-OB5-2	1786	446.5	3.08	11/22/2019	2/20/2020
	S-90-OB5-3	1708	427	2.94	11/22/2019	2/20/2020
	S-90-OB5-4	2087	521.75	3.60	11/22/2019	2/20/2020

	S-90-OB5-5	1871	467.75	3.23	11/22/2019	2/20/2020
	S-90-OB5-6	1739	434.75	3.00	11/22/2019	2/20/2020
Lafarge 2	S-90-LF2-1	2358	589.5	4.06	11/27/2019	2/25/2020
	S-90-LF2-2	2187	546.75	3.77	11/27/2019	2/25/2020
	S-90-LF2-3	2148	537	3.70	11/27/2019	2/25/2020
	S-90-LF2-4	2343	585.75	4.04	11/27/2019	2/25/2020
	S-90-LF2-5	2348	587	4.05	11/27/2019	2/25/2020
	S-90-LF2-6	2315	578.75	3.99	11/27/2019	2/25/2020
Lafarge 3.5	S-90-LF3.5-1	2852	713	4.92	11/27/2019	2/25/2020
	S-90-LF3.5-2	2960	740	5.10	11/27/2019	2/25/2020
	S-90-LF3.5-3	2748	687	4.74	11/27/2019	2/25/2020
	S-90-LF3.5-4	2788	697	4.81	11/27/2019	2/25/2020
	S-90-LF3.5-5	2832	708	4.88	11/27/2019	2/25/2020
	S-90-LF3.5-6	2757	689.25	4.75	11/27/2019	2/25/2020
Biolime 2	S-90-BA2-1	3064	766	5.28	11/29/2019	2/25/2020
	S-90-BA2-2	3316	829	5.72	11/29/2019	2/25/2020
	S-90-BA2-3	3065	766.25	5.28	11/29/2019	2/25/2020
	S-90-BA2-4	2865	716.25	4.94	11/29/2019	2/25/2020
	S-90-BA2-5	2747	686.75	4.73	11/29/2019	2/25/2020
	S-90-BA2-6	2841	710.25	4.90	11/29/2019	2/25/2020
Biolime 3.5	S-90-BA3.5-1	3910	977.5	6.74	11/29/2019	2/25/2020
	S-90-BA3.5-2	3670	917.5	6.33	11/29/2019	2/25/2020
	S-90-BA3.5-3	3720	930	6.41	11/29/2019	2/25/2020
	S-90-BA3.5-4	4210	1052.5	7.26	11/29/2019	2/25/2020
	S-90-BA3.5-5	3780	945	6.52	11/29/2019	2/25/2020
	S-90-BA3.5-6	4050	1012.5	6.98	11/29/2019	2/25/2020
Biolime 5	S-90-BA5-1	5080	1270	8.76	11/29/2019	2/25/2020
	S-90-BA5-2	4960	1240	8.55	11/29/2019	2/25/2020
	S-90-BA5-3	5160	1290	8.89	11/29/2019	2/25/2020
	S-90-BA5-4	5520	1380	9.51	11/29/2019	2/25/2020
	S-90-BA5-5	5190	1297.5	8.95	11/29/2019	2/25/2020
Type O (1:2.5:7.88)	S-90-Type O	7,770	1,943	13.39	12/10/2019	3/09/2020
	S-90-Type O	7,580	1,895	13.07	12/10/2019	3/09/2020
	S-90-Type O	8,830	2,208	15.22	12/10/2019	3/09/2020

Water absorption testing raw data (90 days)

Capillary Water Absorption: St. Astier

t(s): Time
W_0(g): Dry Weight
W_t(g): weight of specimen at time t

ΔW_t(g): weight of absorbed water after time t (W_t - W_0)
A_t (g/cm^2): weight of absorbed water per unit area = (W_t - W_o) X 100/ Area

#	**Specimen ID**	L_1	L_2	(L_1 X L_2) (MM)	W_0(g)
1	A-SA2-1	50.84	51.1	2,598	227.94
2	A-SA2-2	50.9	50.82	2,587	227.45
3	A-SA2-3	50.82	50.9	2,587	224.58
4	A-SA3.5-1	51.27	50.95	2,612	233.37
5	A-SA3.5-2	51.37	51	2,620	231.97
6	A-SA3.5-3	51.83	51.12	2,650	240.27
7	A-SA5-1	51.17	50.95	2,607	233.26
8	A-SA5-2	50.96	51.01	2,599	229.72
9	A-SA5-3	51.13	50.95	2,605	231.1

SA2: 16:50		1 min	3 min	5 min	10 min	15 min	1 hour	2 hour	4 hour	8 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	14,400	28,800	86,400
1	W_t(g)	229.61	231.93	234	236.37	238.5	249.25	257.86	259.17		
	ΔW_t(g)	1.67	3.99	6.06	8.43	10.56	21.31	29.92	31.23		
	A_t	0.06	0.15	0.23	0.32	0.41	0.82	1.15	1.20		
2	W_0(g)	229.97	232.18	233.77	235.61	237.31	245.97	253.56	258.48		
	ΔW_t(g)	2.52	4.73	6.32	8.16	9.86	18.52	26.11	31.03		
	A_t	0.10	0.18	0.24	0.32	0.38	0.72	1.01	1.20		
3	W_0(g)	227.28	229.56	230.98	232.81	234.52	243.38	251.53	255.85		
	ΔW_t(g)	2.7	4.98	6.4	8.23	9.94	18.8	26.95	31.27		
	A_t	0.10	0.19	0.25	0.32	0.38	0.73	1.04	1.21		
A_t (Average)		0.09	0.18	0.24	0.32	0.39	0.75	1.07	1.20		

SA3.5: 16:52		1 min	3 min	5 min	10 min	15 min	1 hour	2 hour	4 hour	8 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	14,400	28,800	86,400
4	W_t(g)	235.32	237.29	238.34	239.95	241.16	247.76	253.44	261.28	266.1	
	ΔW_t(g)	1.95	3.92	4.97	6.58	7.79	14.39	20.07	27.91	32.73	
	A_t	0.07	0.15	0.19	0.25	0.30	0.55	0.77	1.07	1.25	
5	W_0(g)	234.07	235.71	236.49	237.98	239.04	244.7	249.37	255.8	264.3	
	ΔW_t(g)	2.1	3.74	4.52	6.01	7.07	12.73	17.4	23.83	32.33	
	A_t	0.08	0.14	0.17	0.23	0.27	0.49	0.66	0.91	1.23	
6	W_0(g)	242.45	243.84	244.58	246.14	247.15	252.44	256.48	262.14	270.22	
	ΔW_t(g)	2.18	3.57	4.31	5.87	6.88	12.17	16.21	21.87	29.95	
	A_t	0.08	0.13	0.16	0.22	0.26	0.46	0.61	0.83	1.13	
A_t (Average)		0.08	0.14	0.18	0.23	0.28	0.50	0.68	0.93	1.21	

SA 5: 16:56		1 min	3 min	5 min	10 min	15 min	1 hour	2 hour	4 hour	8 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	14,400	28,800	86,400
7	W_t(g)	235.62	238.23	240	242.9	245.37	256.47	264.18	265.3		
	ΔW_t(g)	2.36	4.97	6.74	9.64	12.11	23.21	30.92	32.04		
	A_t	0.09	0.19	0.26	0.37	0.46	0.89	1.19	1.23		
8	W_0(g)	231.7	233.66	234.86	237.03	238.91	247.53	254.61	262.22		
	ΔW_t(g)	1.98	3.94	5.14	7.31	9.19	17.81	24.89	32.5		
	A_t	0.08	0.15	0.20	0.28	0.35	0.69	0.96	1.25		
9	W_0(g)	233.19	235.05	236.37	238.84	240.96	250.86	258.43	263.43		
	ΔW_t(g)	2.09	3.95	5.27	7.74	9.86	19.76	27.33	32.33		
	A_t	0.08	0.15	0.20	0.30	0.38	0.76	1.05	1.24		
A_t (Average)		0.08	0.16	0.22	0.32	0.40	0.78	1.06	1.24		

Capillary Water Absorption: Otterbein

t(s): Time

W_0(g): Dry Weight

W_t(g): weight of specimen at time t

ΔW_t(g): weight of absorbed water after time t (W_t - W_0)

A_t (g/cm^2): weight of absorbed water per unit area = (W_t - W_o) X 100/ Area

#	Specimen ID	L_1	L_2	(L_1 X L_2) (MM)	W_0(g)
1	A-OB2-1	50.73	50.66	2,570	221.72
2	A-OB2-2	51.47	51.63	2,657	224
3	A-OB2-3	50.88	51	2,595	229.66
4	A-OB3.5-1	50.47	50.5	2,549	219.37
5	A-OB3.5-2	50.66	50.52	2,559	223.9
6	A-OB3.5-3	51.04	50.84	2,595	224.34
7	A-OB5-1	52.02	51.45	2,676	242.63
8	A-OB5-2	51.13	51.74	2,645	228.3
9	A-OB5-3	51	51.3	2,616	231.7

		1 min	3 min	5 min	10 min	15 min	1 hour	2 hour	3 hour	4 hour	5 hour	8 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	10,800	14,400	18,000	28,800	86,400
1	W_t(g)	223.46	225.45	226.46	228.23	229.58	237.34	243.8	247.71	248.96	249.13		
	ΔW_t(g)	1.74	3.73	4.74	6.51	7.86	15.62	22.08	25.99	27.24	27.41		
	A_t	0.07	0.15	0.18	0.25	0.31	0.61	0.86	1.01	1.06	1.07		
2	W_0(g)	226.09	228	229.24	231.31	233.13	242.74	250.59	253.2	253.36	253.35		
	ΔW_t(g)	2.09	4	5.24	7.31	9.13	18.74	26.59	29.2	29.36	29.35		
	A_t	0.08	0.15	0.20	0.28	0.34	0.71	1.00	1.10	1.10	1.10		
3	W_0(g)	232.24	233.6	234.37	235.56	236.57	241.87	247.01	251.16	254.6	256.75		
	ΔW_t(g)	2.58	3.94	4.71	5.9	6.91	12.21	17.35	21.5	24.94	27.09		
	A_t	0.10	0.15	0.18	0.23	0.27	0.47	0.67	0.83	0.96	1.04		
A_t (Average)		0.08	0.15	0.19	0.25	0.31	0.59	0.84	0.98	1.04	1.07		

		1 min	3 min	5 min	10 min	15 min	1 hour	2 hour	3 hour	4 hour	5 hour	8 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	10,800	14,400	18,000	28,800	86,400
4	W_t(g)	220.91	222.31	223.64	225.21	226.57	233.93	240.26	244.89	247.35			
	ΔW_t(g)	1.54	2.94	4.27	5.84	7.2	14.56	20.89	25.52	27.98	-219.37		
	A_t	0.06	0.12	0.17	0.23	0.28	0.57	0.82	1.00	1.10	-8.61		
5	W_0(g)	225.41	226.65	227.99	229.67	231.24	238.87	245.6	250.38	252.28			
	ΔW_t(g)	1.51	2.75	4.09	5.77	7.34	14.97	21.7	26.48	28.38	-223.9		
	A_t	0.06	0.11	0.16	0.23	0.29	0.58	0.85	1.03	1.11	-8.75		
6	W_0(g)	225.99	227.05	228.15	229.68	231.22	238.65	245.41	250.2	252.64			
	ΔW_t(g)	1.65	2.71	3.81	5.34	6.88	14.31	21.07	25.86	28.3	-224.34		
	A_t	0.06	0.10	0.15	0.21	0.27	0.55	0.81	1.00	1.09	-8.65		
A_t (Average)		0.06	0.11	0.16	0.22	0.28	0.57	0.83	1.01	1.10	-8.67		

		1 min	3 min	5 min	10 min	15 min	1 hour	2 hour	3 hour	4 hour	5 hour	8 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	10,800	14,400	18,000	28,800	86,400
7	W_t(g)	244.94	246.64	247.57	249.22	250.52	258.02	265.36	270.18	272.73	273.35		
	ΔW_t(g)	2.31	4.01	4.94	6.59	7.89	15.39	22.73	27.55	30.1	30.72		
	A_t	0.09	0.15	0.18	0.25	0.29	0.58	0.85	1.03	1.12	1.15		
8	W_0(g)	230.51	231.74	232.64	234.24	235.55	243.5	251.04	255.78	258.42	259.14		
	ΔW_t(g)	2.21	3.44	4.34	5.94	7.25	15.2	22.74	27.48	30.12	30.84		
	A_t	0.08	0.13	0.16	0.22	0.27	0.57	0.86	1.04	1.14	1.17		
9	W_0(g)	233.99	235.26	236.19	238.04	239.42	247.91	256.17	261.39	262.53	263		
	ΔW_t(g)	2.29	3.56	4.49	6.34	7.72	16.21	24.47	29.69	30.83	31.3		
	A_t	0.09	0.14	0.17	0.24	0.30	0.62	0.94	1.13	1.18	1.20		
A_t (Average)		0.09	0.14	0.17	0.24	0.29	0.59	0.88	1.07	1.15	1.17		

Capillary Water Absorption: Lafarge & Type O

t(s): Time

W_0(g): Dry Weight

W_t(g): weight of specimen at time t

ΔW_t(g): weight of absorbed water after time t (W_t - W_0)

A_t (g/cm^2): weight of absorbed water per unit area = (W_t - W_o) X 100/ Area

#	Specimen ID	L_1	L_2	(L_1 X L_2) (MM)	W_0(g)
1	A-LF2-1	50.63	51.12	2,588	228.55
2	A-LF2-2	51.35	51.35	2,637	226.95
3	A-LF2-3	50.9	51.06	2,599	224.75
4	A-LF3.5-1	51.16	51.1	2,614	212.05
5	A-LF3.5-2	51.36	50.73	2,605	220.48
6					
7	A-T/O-1	51.02	51.06	2,605	240.78
8	A-T/O-2	51	51.01	2,602	236.91
9	A-T/O-3	51	51.05	2,604	239.92

		1 min	3 min	5 min	10 min	15 min	70 min	2 hour	3 hour	4 hour	6 hour	8 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	10,800	14,400	21,600	28,800	86,400
1	W_t(g)	229.15	229.81	230.4	231.38	232.51	238.59	242.26	245.81	248.66			
	ΔW_t(g)	0.6	1.26	1.85	2.83	3.96	10.04	13.71	17.26	20.11	-228.55		
	A_t	0.02	0.05	0.07	0.11	0.15	0.39	0.53	0.67	0.78	-8.83		
2	W_0(g)	227.61	228.17	228.62	229.58	230.68	237.15	241.75	246.7	251.07			
	ΔW_t(g)	0.66	1.22	1.67	2.63	3.73	10.2	14.8	19.75	24.12	-226.95		
	A_t	0.03	0.05	0.06	0.10	0.14	0.39	0.56	0.75	0.91	-8.61		
3	W_0(g)	225.59	226.64	227.38	229	230.71	241.8	249.19	254.93	255.6			
	ΔW_t(g)	0.84	1.89	2.63	4.25	5.96	17.05	24.44	30.18	30.85	-224.75		
	A_t	0.03	0.07	0.10	0.16	0.23	0.66	0.94	1.16	1.19	-8.65		
A_t (Average)		0.03	0.06	0.08	0.12	0.17	0.48	0.68	0.86	0.96	-8.70		

		1 min	3 min	5 min	10 min	15 min	70 min	2 hour	3 hour	4 hour	6 hour	8 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	10,800	14,400	21,600	28,800	86,400
4	W_t(g)	213.09	213.99	214.74	216.27	217.49	226.28	232.06	237.64	241.45			
	ΔW_t(g)	1.04	1.94	2.69	4.22	5.44	14.23	20.01	25.59	29.4	-212.05		
	A_t	0.04	0.07	0.10	0.16	0.21	0.54	0.77	0.98	1.12	-8.11		
5	W_0(g)	222.03	223.36	224.34	226.38	228.02	238.95	245.19	250.8	251.89			
	ΔW_t(g)	1.55	2.88	3.86	5.9	7.54	18.47	24.71	30.32	31.41	-220.48		
	A_t	0.06	0.11	0.15	0.23	0.29	0.71	0.95	1.16	1.21	-8.46		
6	W_0(g)												
	ΔW_t(g)	0	0	0	0	0	0	0	0	0	0		
	A_t	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
A_t (Average)		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		

		1 min	3 min	5 min	10 min	15 min	1 hour	2 hour	3 hour	4 hour	6 hour	8 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	10,800	14,400	21,600	28,800	86,400
7	W_t(g)	240.94	241	241.13	241.34	241.59	243.87	247.38		248.71	250.94		
	ΔW_t(g)	0.16	0.22	0.35	0.56	0.81	3.09	6.6		7.93	10.16		
	A_t	0.01	0.01	0.01	0.02	0.03	0.12	0.25		0.30	0.39		
8	W_0(g)	237.05	237.16	237.3	237.56	237.85	240.72	244.71		246.08	248.43		
	ΔW_t(g)	0.14	0.25	0.39	0.65	0.94	3.81	7.8		9.17	11.52		
	A_t	0.01	0.01	0.01	0.02	0.04	0.15	0.30		0.35	0.44		
9	W_0(g)	240.02	240.11	240.24	240.43	240.71	243.15	246.95		248.36	250.61		
	ΔW_t(g)	0.1	0.19	0.32	0.51	0.79	3.23	7.03		8.44	10.69		
	A_t	0.00	0.01	0.01	0.02	0.03	0.12	0.27		0.32	0.41		
A_t (Average)		0.01	0.01	0.01	0.02	0.03	0.13	0.27		0.33	0.41		

Capillary Water Absorption: Biolime

t(s): Time
W_0(g): Dry Weight
W_t(g): weight of specimen at time t

ΔW_t(g): weight of absorbed water after time t (W_t - W_0)
A_t (g/cm^2): weight of absorbed water per unit area = (W_t - W_o) X 100/ Area

#	Specimen ID	L_1	L_2	(L_1 X L_2) (MM)	W_0(g)
1	A-BL2-1	50.45	50.97	2,571	224.89
2	A-BL2-2	51.04	50.97	2,602	228.59
3	A-BL2-3	51.29	50.91	2,611	229.83
4	A-BL3.5-1	50.18	50.29	2,524	228.84
5	A-BL3.5-2	51.2	50.67	2,594	236.29
6	A-BL3.5-3	50.95	50.67	2,582	228.19
7	A-BL5-1	51.2	51	2,611	240.29
8	A-BL5-2	51.07	51.56	2,633	238.98
9	A-BL5-3	50.88	51.41	2,616	237.26

		1 min	3 min	5 min	10 min	15 min	1 hour	2 hour	3:20	4 hour	5 hour	6 hour	8 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	10,800	14,400	28,800	21,600	28,800	86,400
1	W_t(g)	226.33	226.6	226.92	227.64	228.16	232.24	236.58	241.37	243.41	246.54			
	ΔW_t(g)	1.44	1.71	2.03	2.75	3.27	7.35	11.69	16.48	18.52	21.65			
	A_t	0.06	0.07	0.08	0.11	0.13	0.29	0.45	0.64	0.72	0.84			
2	W_0(g)	230.01	230.48	231.01	232.04	232.86	238.27	243.74	249.71	252.16	255.54			
	ΔW_t(g)	1.42	1.89	2.42	3.45	4.27	9.68	15.15	21.12	23.57	26.95			
	A_t	0.05	0.07	0.09	0.13	0.16	0.37	0.58	0.81	0.91	1.04			
3	W_0(g)	231.21	231.61	231.88	232.55	233.06	236.8	241.24	246.54	248.84	253.69			
	ΔW_t(g)	1.38	1.78	2.05	2.72	3.23	6.97	11.41	16.71	19.01	23.86			
	A_t	0.05	0.07	0.08	0.10	0.12	0.27	0.44	0.64	0.73	0.91			
A_t (Average)		0.05	0.07	0.08	0.11	0.14	0.31	0.49	0.70	0.78	0.93			

		1 min	3 min	5 min	10 min	15 min	1 hour	2 hour	3 hour	4 hour	6 hour	8 hour	10 hour	24 hour
#	t(s)	60	180	300	600	900	3,600	7,200	10,800	14,400	28,800	21,600	28,800	86,400
4	W_t(g)	229.8	230.26	230.53	231.08	231.55	234.13	236.57	238.61	239.45	241.43			248.76
	ΔW_t(g)	0.96	1.42	1.69	2.24	2.71	5.29	7.73	9.77	10.61	12.59			19.92
	A_t	0.04	0.06	0.07	0.09	0.11	0.21	0.31	0.39	0.42	0.50			0.79
5	W_0(g)	237.12	237.62	237.94	238.63	239.16	234.23	245	247.44	248.57	251.04			257.92
	ΔW_t(g)	0.83	1.33	1.65	2.34	2.87	-2.06	8.71	11.15	12.28	14.75			21.63
	A_t	0.03	0.05	0.06	0.09	0.11	-0.08	0.34	0.43	0.47	0.57			0.83
6	W_0(g)	229.17	229.68	230.05	230.66	231.22	234.3	237.25	237.96	241.48	243.74			252.11
	ΔW_t(g)	0.98	1.49	1.86	2.47	3.03	6.11	9.06	9.77	13.29	15.55			23.92
	A_t	0.04	0.06	0.07	0.10	0.12	0.24	0.35	0.38	0.51	0.60			0.93
A_t (Average)		0.04	0.06	0.07	0.09	0.11	0.12	0.33	0.40	0.47	0.56			0.85

		1 min	3 min	5 min	10 min	15 min	1 hour	2 hour	3:20	4 hour	6 hour	8 hour	11 hour	24 hour
#	t(s)													0
7	W_t(g)	242.05	242.77	243.32	243.95	244.4	246.56	248.01	249.02	249.35	250.15			252.58
	ΔW_t(g)	1.76	2.48	3.03	3.66	4.11	6.27	7.72	8.73	9.06	9.86			12.29
	A_t	0.07	0.09	0.12	0.14	0.16	0.24	0.30	0.33	0.35	0.38			0.47
8	W_0(g)	240.59	241.56	242.34	243.34	244.08	247.59	250.04	251.88	252.5	254.16			258.48
	ΔW_t(g)	1.61	2.58	3.36	4.36	5.1	8.61	11.06	12.9	13.52	15.18			19.5
	A_t	0.06	0.10	0.13	0.17	0.19	0.33	0.42	0.49	0.51	0.58			0.74
9	W_0(g)	239.05	239.86	240.03	241.13	241.64	243.98	245.72	247.13	247.63	248.93			254.83
	ΔW_t(g)	1.79	2.6	2.77	3.87	4.38	6.72	8.46	9.87	10.37	11.67			17.57
	A_t	0.07	0.10	0.11	0.15	0.17	0.26	0.32	0.38	0.40	0.45			0.67
A_t (Average)		0.07	0.10	0.12	0.15	0.17	0.27	0.35	0.40	0.42	0.47			0.63

WVT raw data: Change of weight over time (St. Astier and Otterbein)

	SA 2			SA 3.5			SA5			OB 2			OB 3.5		OB 5		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	1	2	3
sample diameter (mm)	51.91	52.32	51.29	51.64	52.32	51.83	52.39	52.01	52.51	51.55	51.73	52.77	52.26	52.07	52.08	52.91	52.15
sample area (m2)	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021	0.0022	0.0021	0.0022	0.0021	0.0021	0.0022	0.0021	0.0021	0.0021	0.0022	0.0021
sample weight	134.12	136.38	135.46	138.13	139.92	135.51	133.75	134.85	134.89	137.76	132.95	134.86	135.01	136.16	136.74	136.32	133.72

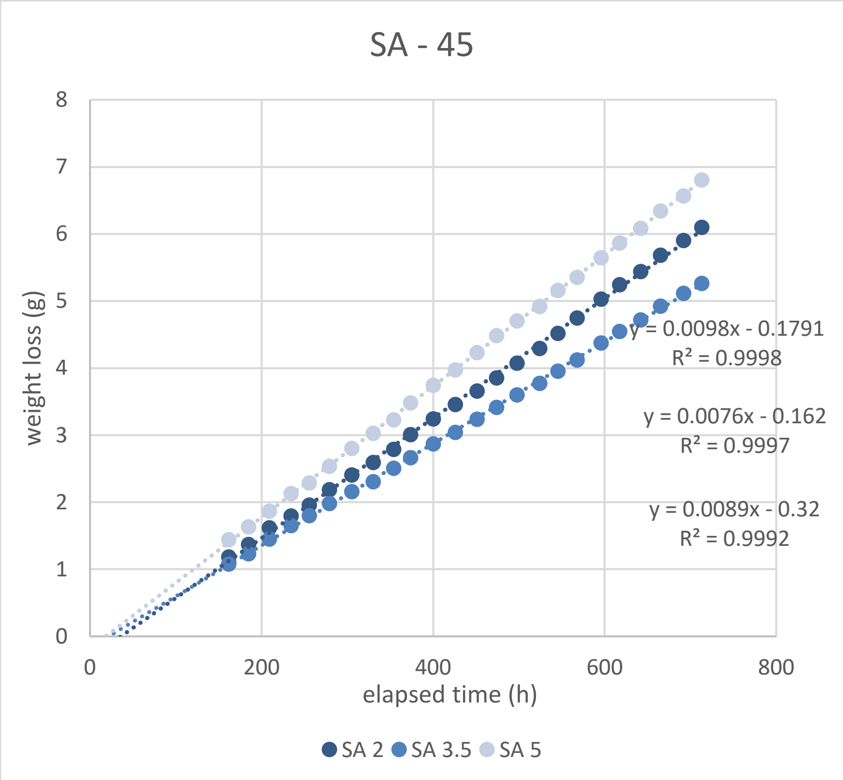
							SA 2			SA 3.5			SA5			OB 2			OB 3.5		OB 5	
Date	**Time**		**Elapse**	**Time**	**Temp. (°**	**RH (%)**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**1**	**2**
02-06-20	1:19	2020-02-06 1:19		0.00	23.60	49%	134.12	136.38	135.46	138.13	139.92	135.51	133.75	134.85	134.89	137.76	132.95	134.86	135.01	136.16	136.74	136.32
02-06-20	20:20	2020-02-06 20:20	19.0	19.0	23.10	58%	134.08	136.34	135.40	138.11	139.87	135.46	133.71	134.81	134.85	137.71	132.89	134.78	134.94	136.12	136.67	136.27
02-07-20	17:30	2020-02-07 17:30	40.2	21.2	23.80	56%	133.95	136.21	135.32	137.93	139.84	135.32	133.64	134.71	134.64	137.60	132.72	134.58	134.77	135.85	136.58	136.13
02-08-20	17:53	2020-02-08 17:53	64.6	24.4	24.00	56%	133.73	135.98	135.06	137.73	139.58	135.09	133.33	134.39	134.35	137.25	132.41	134.35	134.53	135.59	136.32	135.92
02-09-20	18:20	2020-02-09 18:20	89.0	24.5	23.20	54%	133.56	135.81	134.89	137.62	139.44	134.89	133.09	134.12	134.17	137.02	132.24	134.13	134.35	135.41	136.04	135.78
02-10-20	19:37	2020-02-10 19:37	114.3	25.3	23.43	51%	133.39	135.60	134.66	137.47	139.24	134.72	132.85	133.90	133.89	136.78	131.99	133.93	134.12	135.21	135.82	135.55
02-11-20	17:48	2020-02-11 17:48	136.5	22.2	23.45	52%	133.18	135.35	134.45	137.28	139.05	134.53	132.63	133.62	133.65	136.45	131.77	133.73	133.89	134.99	135.53	135.36
02-12-20	19:04	2020-02-12 19:04	161.8	25.3	23.72	51%	133.01	135.16	134.24	137.10	138.88	134.35	132.42	133.35	133.39	136.22	131.53	133.46	133.70	134.76	135.26	135.18
02-13-20	17:55	2020-02-13 17:55	184.6	22.9	23.22	52%	132.80	134.97	134.08	136.94	138.75	134.18	132.24	133.07	133.28	136.01	131.31	133.26	133.54	134.61	134.90	135.04
02-14-20	18:19	2020-02-14 18:19	209.0	24.4	23.17	51%	132.58	134.72	133.81	136.71	138.53	133.96	132.00	132.86	133.03	135.78	131.07	133.02	133.31	134.35	134.52	134.78
02-15-20	19:28	2020-02-15 19:28	234.2	25.2	23.20	51%	132.40	134.53	133.65	136.47	138.37	133.77	131.77	132.64	132.69	135.50	130.76	132.82	133.11	134.15	134.28	134.60
02-16-20	16:43	2020-02-16 16:43	255.4	21.2	23.53	52%	132.22	134.38	133.49	136.32	138.21	133.63	131.65	132.46	132.52	135.37	130.64	132.67	132.96	134.02	134.11	134.36
02-17-20	16.28	2020-02-17 16:28	279.2	23.8	23.58	51%	132.02	134.13	133.25	136.14	138.08	133.40	131.40	132.29	132.19	135.05	130.36	132.44	132.72	133.73	133.83	134.09
02-18-20	18:37	2020-02-18 18:37	305.3	26.1	23.22	52%	131.82	133.86	133.06	135.94	137.91	133.24	131.19	132.00	131.89	134.84	130.08	132.18	132.47	133.54	133.64	133.75
02-19-20	19:33	2020-02-19 19:33	330.2	24.9	23.00	52%	131.64	133.63	132.91	135.77	137.78	133.09	130.98	131.80	131.63	134.57	129.88	131.93	132.21	133.32	133.45	133.56
02-20-20	19:10	2020-02-20 19:10	353.9	23.6	23.20	51%	131.43	133.45	132.71	135.58	137.58	132.88	130.81	131.59	131.41	134.34	129.68	131.72	132.01	133.10	133.21	133.38
02-21-20	15:10	2020-02-21 15:10	373.9	20.0	24.02	0.51	131.27	133.18	132.48	135.39	137.45	132.73	130.60	131.36	131.09	134.11	129.44	131.54	131.82	132.91	132.97	133.14
02-22-20	17:35	2020-02-22 17:35	400.3	26.4	23.75	0.51	131.03	132.89	132.31	135.18	137.26	132.51	130.39	131.03	130.84	133.86	129.15	131.30	131.58	132.68	132.76	132.92
02-23-20	19:19	2020-02-23 19:19	426.0	25.7	24.40	0.50	130.83	132.63	132.12	135.01	137.10	132.32	130.16	130.78	130.63	133.64	128.91	131.08	131.36	132.49	132.50	132.72
02-24-20	20:30	2020-02-24 20:30	451.2	25.2	25.17	0.51	130.64	132.43	131.92	134.82	136.91	132.11	129.90	130.52	130.37	133.42	128.63	130.82	131.17	132.26	132.22	132.48
02-25-20	19:08	2020-02-25 19:08	473.8	22.6	25.85	0.51	130.44	132.25	131.70	134.65	136.74	131.92	129.68	130.28	130.08	133.17	128.39	130.59	130.93	132.01	132.04	132.23
02-26-20	19:00	2020-02-26 19:00	497.7	23.9	22.98	0.51	130.22	132.00	131.52	134.47	136.55	131.74	129.44	130.07	129.86	132.92	128.11	130.37	130.69	131.80	131.80	132.03
02-27-20	21:26	2020-02-27 21:26	524.1	26.4	23.97	0.50	130.05	131.70	131.33	134.29	136.40	131.55	129.24	129.86	129.63	132.72	127.85	130.15	130.50	131.58	131.60	131.88
02-28-20	18:44	2020-02-28 18:44	545.4	21.3	24.85	0.50	129.87	131.44	131.10	134.10	136.24	131.36	128.99	129.60	129.42	132.47	127.58	129.93	130.26	131.36	131.35	131.63
02-29-20	17:13	2020-02-29 17:13	567.9	22.5	24.78	0.50	129.67	131.18	130.86	133.95	136.06	131.19	128.84	129.40	129.19	132.29	127.32	129.64	130.08	131.15	131.16	131.50
03-01-20	21:00	2020-03-01 21:00	595.7	27.8	23.85	0.51	129.43	130.94	130.50	133.65	135.86	130.93	128.56	129.10	128.89	132.00	127.08	129.37	129.81	130.89	130.83	131.25
03-02-20	18:41	2020-03-02 18:41	617.4	21.7	24.33	0.51	129.22	130.72	130.29	133.45	135.71	130.76	128.36	128.90	128.63	131.79	126.83	129.16	129.57	130.70	130.58	131.04
03-03-20	19:22	2020-03-03 19:22	642.0	24.7	24.90	0.49	129.03	130.54	130.06	133.23	135.55	130.62	128.16	128.71	128.36	131.62	126.62	128.96	129.37	130.51	130.37	130.84
03-04-20	18:16	2020-03-04 18:16	665.0	22.9	24.90	0.51	128.82	130.32	129.76	133.02	135.35	130.42	127.91	128.43	128.12	131.21	126.40	128.74	129.13	130.27	130.08	130.46
03-05-20	21:19	2020-03-05 21:19	692.0	27.0	23.83	0.51	128.59	130.09	129.57	132.83	135.18	130.20	127.72	128.19	127.87	130.85	126.08	128.47	128.89	130.03	129.78	130.07
03-06-20	18:40	2020-03-06 18:40	713.4	21.4	24.28	0.51	128.42	129.92	129.32	132.68	135.06	130.03	127.53	127.89	127.65	130.56	125.87	128.26	128.72	129.85	129.55	129.75

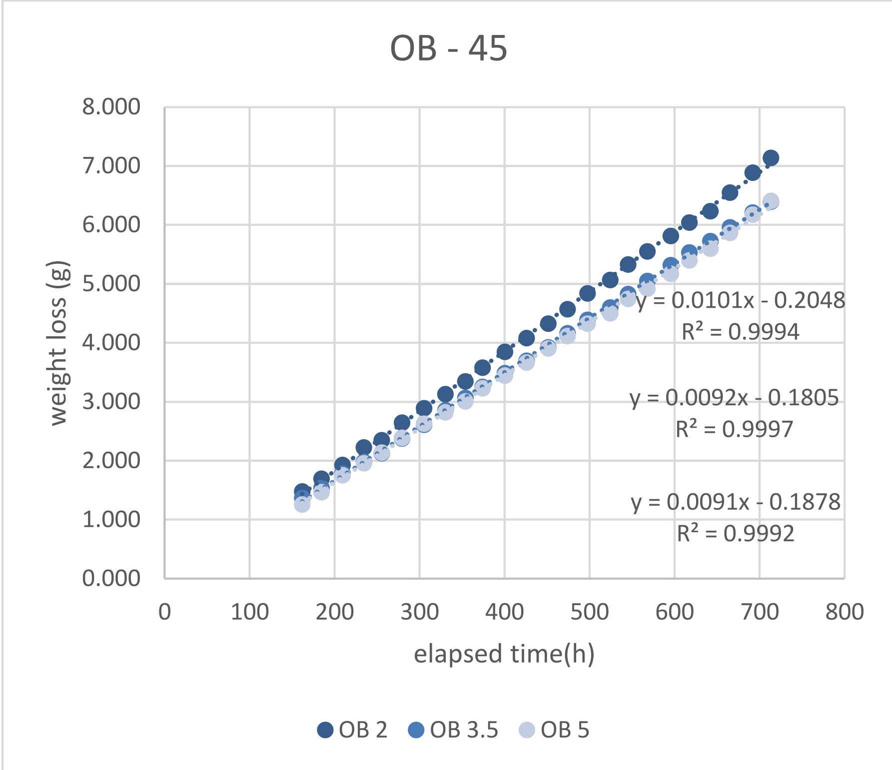
WVT raw data: Change of weight over time (Lafarge, Biolime, Type O)

	BL 2			BL 3.5			BL 5			LF 2			LF 3.5			T/O		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
sample diameter (mm)	52.57	52.66	52.56	52.35	52.23	52.22	52.77	51.95	51.87	51.76	53.52	51.95	52.42	52.61	52.06	52.15	52.43	52.85
sample area (m2)	0.0022	0.0022	0.0022	0.0022	0.0021	0.0021	0.0022	0.0021	0.0021	0.0021	0.0022	0.0021	0.0022	0.0022	0.0021	0.0021	0.0022	0.0022
sample weight	138.73	136.45	136.66	138.57	137.62	137.33	141.61	142.7	139.07	139.71	138.06	136.77	135.01	136.75	139.6	142.17	142.01	146.23

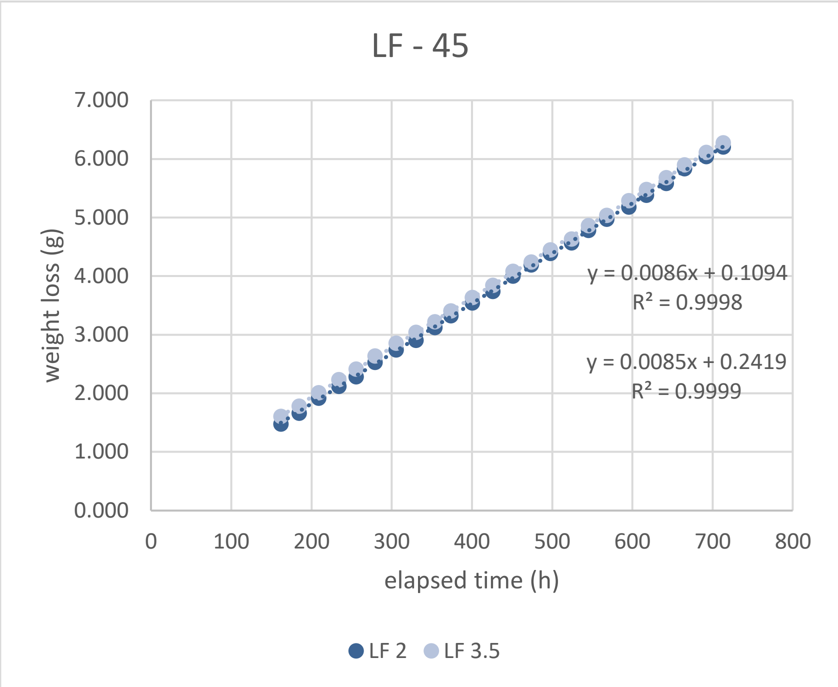
							BL 2			BL 3.5			BL 5			LF 2			LF 3.5			T/O		
Date	Time		Elapse	Time	Temp. (°	RH (%)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
02-06-20	1:19	2020-02-06 1:19		0.00	23.60	49%	138.73	136.45	136.66	138.57	137.62	137.33	141.61	142.70	139.07	139.71	138.06	136.77	135.01	136.75	139.60	142.17	142.01	146.23
02-06-20	20:20	2020-02-06 20:20	19.0	19.0	23.10	58%	138.70	136.42	136.62	138.52	137.58	137.32	141.55	142.66	139.01	139.56	137.86	136.66	134.78	136.63	139.42	141.93	141.86	146.09
02-07-20	17:30	2020-02-07 17:30	40.2	21.2	23.80	56%	138.52	136.32	136.41	138.35	137.42	137.26	141.39	142.56	138.91	139.33	137.68	136.61	134.64	136.53	139.18	141.89	141.76	145.94
02-08-20	17:53	2020-02-08 17:53	64.6	24.4	24.00	56%	138.29	136.05	136.17	138.10	137.24	137.00	141.07	142.31	138.62	139.07	137.36	136.34	134.25	136.20	138.89	141.57	141.47	145.66
02-09-20	18:20	2020-02-09 18:20	89.0	24.5	23.20	54%	138.06	135.90	135.97	137.95	137.03	136.80	140.85	142.13	138.45	138.87	137.11	136.11	134.02	135.96	138.66	141.30	141.34	145.43
02-10-20	19:37	2020-02-10 19:37	114.3	25.3	23.43	51%	137.84	135.68	135.77	137.69	136.82	136.58	140.65	141.91	138.23	138.64	136.86	135.91	133.81	135.69	138.43	141.07	141.09	145.20
02-11-20	17:48	2020-02-11 17:48	136.5	22.2	23.45	52%	137.63	135.47	135.54	137.48	136.58	136.35	140.39	141.69	138.00	138.42	136.62	135.72	133.62	135.45	138.18	140.87	140.94	145.00
02-12-20	19:04	2020-02-12 19:04	161.8	25.3	23.72	51%	137.44	135.26	135.30	137.26	136.36	136.04	140.19	141.46	137.77	138.23	136.43	135.45	133.40	135.19	137.95	140.67	140.75	144.78
02-13-20	17:55	2020-02-13 17:55	184.6	22.9	23.22	52%	137.23	135.08	135.11	137.08	136.06	135.84	140.00	141.29	137.56	138.06	136.28	135.21	133.24	135.01	137.77	140.48	140.56	144.64
02-14-20	18:19	2020-02-14 18:19	209.0	24.4	23.17	51%	137.00	134.90	134.84	136.83	135.78	135.61	139.76	141.06	137.35	137.82	136.04	134.93	133.00	134.78	137.55	140.23	140.39	144.46
02-15-20	19:28	2020-02-15 19:28	234.2	25.2	23.20	51%	136.79	134.65	134.65	136.63	135.52	135.42	139.54	140.83	137.13	137.61	135.86	134.71	132.79	134.52	137.35	140.08	140.22	144.29
02-16-20	16:43	2020-02-16 16:43	255.4	21.2	23.53	52%	136.55	134.52	134.47	136.48	135.30	135.23	139.38	140.68	136.99	137.45	135.74	134.50	132.65	134.29	137.18	139.93	140.07	144.17
02-17-20	16.28	2020-02-17 16:28	279.2	23.8	23.58	51%	136.33	134.30	134.14	136.28	135.07	134.99	139.15	140.40	136.75	137.23	135.50	134.22	132.42	134.09	136.94	139.68	139.86	143.94
02-18-20	18:37	2020-02-18 18:37	305.3	26.1	23.22	52%	136.09	134.09	133.89	136.04	134.83	134.84	138.90	140.20	136.55	137.00	135.32	133.99	132.24	133.83	136.73	139.52	139.69	143.75
02-19-20	19:33	2020-02-19 19:33	330.2	24.9	23.00	52%	135.85	133.94	133.67	135.84	134.63	134.65	138.76	139.99	136.33	136.83	135.18	133.81	132.08	133.56	136.59	139.37	139.54	143.62
02-20-20	19:10	2020-02-20 19:10	353.9	23.6	23.20	51%	135.63	133.75	133.48	135.60	134.41	134.43	138.49	139.78	136.13	136.62	135.00	133.55	131.85	133.44	136.40	139.16	139.37	143.42
02-21-20	15:10	2020-02-21 15:10	373.9	20.0	24.02	0.51	135.43	133.52	133.28	135.37	134.21	134.23	138.24	139.59	135.88	136.44	134.78	133.35	131.67	133.24	136.23	138.94	139.18	143.22
02-22-20	17:35	2020-02-22 17:35	400.3	26.4	23.75	0.51	135.16	133.32	133.03	135.17	133.97	134.01	138.01	139.36	135.66	136.22	134.57	133.12	131.48	132.96	136.01	138.77	138.99	143.05
02-23-20	19:19	2020-02-23 19:19	426.0	25.7	24.40	0.50	134.97	133.12	132.80	134.96	133.75	133.79	137.81	139.12	135.45	136.04	134.40	132.88	131.28	132.75	135.80	138.57	138.82	142.88
02-24-20	20:30	2020-02-24 20:30	451.2	25.2	25.17	0.51	134.72	132.88	132.55	134.73	133.49	133.55	137.56	138.90	135.22	135.83	134.13	132.58	131.03	132.50	135.58	138.35	138.63	142.66
02-25-20	19:08	2020-02-25 19:08	473.8	22.6	25.85	0.51	134.49	132.66	132.33	134.51	133.29	133.36	137.39	138.72	134.99	135.62	133.93	132.42	130.88	132.34	135.42	138.15	138.44	142.47
02-26-20	19:00	2020-02-26 19:00	497.7	23.9	22.98	0.51	134.26	132.43	132.12	134.30	133.04	133.10	137.17	138.46	134.78	135.44	133.75	132.19	130.67	132.13	135.21	137.95	138.29	142.31
02-27-20	21:26	2020-02-27 21:26	524.1	26.4	23.97	0.50	134.05	132.26	131.91	134.08	132.82	132.90	136.96	138.18	134.57	135.26	133.60	131.98	130.50	131.92	135.03	137.81	138.13	142.15
02-28-20	18:44	2020-02-28 18:44	545.4	21.3	24.85	0.50	133.79	132.03	131.68	133.84	132.62	132.69	136.69	137.91	134.31	135.04	133.39	131.77	130.26	131.70	134.81	137.60	137.93	141.99
02-29-20	17:13	2020-02-29 17:13	567.9	22.5	24.78	0.50	133.62	131.89	131.45	133.67	132.36	132.50	136.49	137.70	134.15	134.83	133.25	131.55	130.10	131.50	134.65	137.46	137.79	141.82
03-01-20	21:00	2020-03-01 21:00	595.7	27.8	23.85	0.51	133.32	131.66	131.22	133.40	132.12	132.31	136.22	137.46	133.90	134.66	133.00	131.34	129.83	131.26	134.41	137.25	137.56	141.62
03-02-20	18:41	2020-03-02 18:41	617.4	21.7	24.33	0.51	133.14	131.49	130.98	133.18	131.85	132.07	136.02	137.27	133.60	134.45	132.86	131.08	129.64	131.05	134.23	137.09	137.42	141.44
03-03-20	19:22	2020-03-03 19:22	642.0	24.7	24.90	0.49	132.90	131.30	130.79	132.98	131.66	131.86	135.78	137.08	133.35	134.32	132.71	130.76	129.45	130.83	134.03	136.88	137.24	141.31
03-04-20	18:16	2020-03-04 18:16	665.0	22.9	24.90	0.51	132.66	131.13	130.59	132.73	131.36	131.67	135.60	136.88	133.08	134.07	132.46	130.51	129.20	130.63	133.83	136.74	137.08	141.14
03-05-20	21:19	2020-03-05 21:19	692.0	27.0	23.83	0.51	132.43	130.98	130.32	132.47	131.07	131.44	135.36	136.65	132.89	133.87	132.31	130.24	129.05	130.37	133.60	136.54	136.88	140.93
03-06-20	18:40	2020-03-06 18:40	713.4	21.4	24.28	0.51	132.23	130.73	130.12	132.24	130.82	131.28	135.15	136.47	132.66	133.73	132.13	130.06	128.89	130.20	133.44	136.39	136.70	140.81

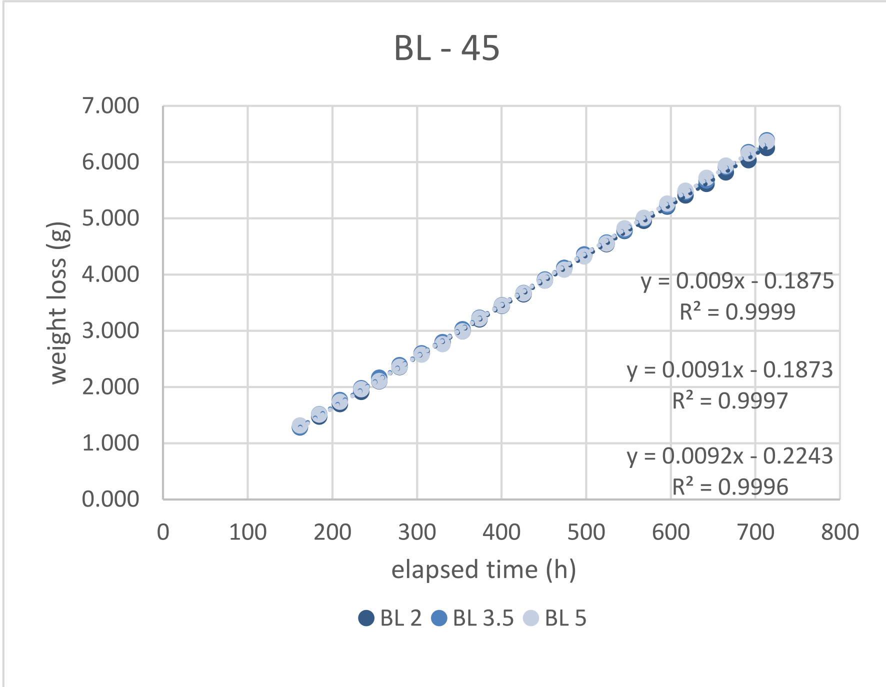
WVT raw data: Weight loss over time (St. Astier, Otterbein)



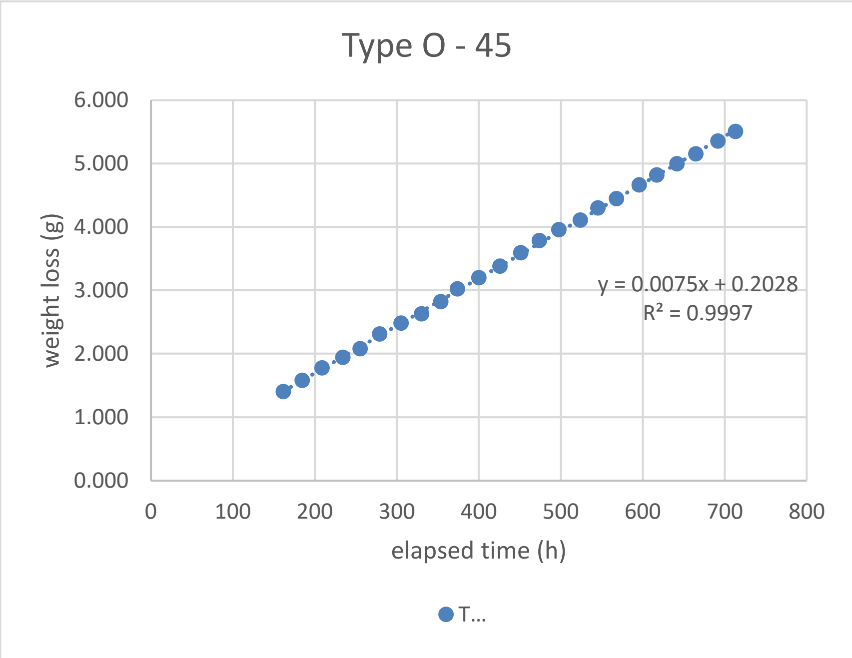


WVT raw data: Weight loss over time (Lafarge, Biolime)





WVT Raw Data: Weight loss over time (Type O)



Appendix B: Product Data Sheet

St. Astier NHL 2 Product Data: http://www.stastier.co.uk/nhl/data/nhl2.htm

Pure and Natural Hydraulic Lime (NHL 2) Product Data

St Astier Natural Hydraulic Limes (NHL)

Conforms to European Norm EN 459 and BS 459
Strength factor: 2 (Feebly hydraulic)
Residue @ 0.09 mm: 5%
Density (volumetric weight) : typical 500 gr. / litre
Available (free) lime $Ca(OH)_2$ after slaking: 50-55%
Packing: 25kg. Bags

Contains no additives
Whiteness index: 76
Surface cover (cm^2 per gram): 11000
Expansion : < 1mm
Residue of quick lime after slaking: <1%
Shelf life: 8-12 months kept sealed and dry

MORTARS	Compressive strength - N/mm^2				Elasticity Moduli (Mpa)		
MIX RATIO	EN459*	1 : 2	1:2.5	1 : 3	1 : 2	1 : 2.5	1 : 3
7 DAYS		0.62	0.53	0.47			
28 DAYS	2.00*	1.48	1.36	1.25	9025	9800	9000
6 MONTHS		3.84	3.00	2.88	12600	12030	11800
12 MONTHS		4.00	2.90	2.90	12515	12030	11900
24 MONTHS		4.25	3.00	2.75	13375	12000	11750
Consumption for $1m^3$ of mortar (kg. +/- 10%)		280	224	168			
* EN/BS 459 (mortar ratio 1:1 by volume with ISO 679 Sand)							

Mixing: can be mixed in cement mixers.
Application by spray gun: possible. Please consult us.

Working temperatures: not below 8°C or above 30°C. Make sure that high suction materials are thoroughly dampened before application. Avoid rapid drying due to high temperatures or strong winds by curing with a light water mist several times a day if necessary. Protect from frost, rain, direct sun and strong wind
See "Protecting Lime Mortar".

SUITABLE FOR LATH WORK/INJECTION/GROUTING: see relevant sheets.
Reworking: possible within 24 hours.
Mortar composition
MASONRY/POINTING: 1 VOLUME OF NHL 2 : 2 VOLUMES OF SAND
Choose well graded sands (3mm: 75microns).
See also Applications & Good Working Practices - Sands for Lime Mortars

RENDERING:
On earth or friable supports, after preparation and cleaning, dampen with a 1:20 solution of NHL2/water applied in 2 coats.

A. Scratch coat (3 - 4 mm) 3 VOLUMES OF NHL 2 5 VOLUMES OF SAND

This coat is applied by casting on to a still damp but not over saturated support and is left as cast to provide good keying.

B. Undercoat (15-20 mm) 1 VOLUME OF NHL 2 2 VOLUMES OF SAND

Can be applied in 2 passes of min. 1cm. Second pass only after first is reasonably dry.

C. Finishing (5mm) 1 VOLUME OF NHL 2 2.5 VOLUMES OF SAND

The dosage / thickness may vary in accordance with the desired finish and the sand used. In smooth floated finishes if very fine sands containing clay are used the binder (NHL) quantity will be reduced.

For further Guidance, contact your St Astier Distributor.

SAINT-ASTIER

St. Astier NHL 3.5 Product Data: http://www.stastier.co.uk/nhl/data/nhl35.htm

Pure and Natural Hydraulic Lime (NHL 3.5) Product Data

St Astier Natural Hydraulic Limes (NHL)

Conforms to European Norms EN 459 and BS 459
Strength factor: 3.5 (Moderately hydraulic)
Residue @ 0.09 mm: 6.5%
Density (volumetric weight) : typical 650gr / litre
Available (free) lime after slaking $Ca(OH)_2$: 25% +
Packing: 25kg. Bags

Contains no additives.
Whiteness index: 72
Surface cover (cm2pergram): 9000
Expansion : < 1mm
Residue of quick lime after slaking: < 1%
Shelf life: 8-12 months kept sealed and dry

MORTARS	Compressive strengthN/mm^2				Elasticity Moduli (Mpa)		
MIX RATIO	EN459*	1 : 2	1 : 2.5	1 : 3	1 : 2	1:2.5	1 :3
7 DAYS		0.75	0.57	0.53			
28 DAYS	3.5*	1.88	1.47	1.34	9010	9000	8070
6 MONTHS		7.1	5.34	3.94	15260	13501	13150
12 MONTHS		7.5	5.90	3.90	15280	13620	13150
24 MONTHS		8.63	6.00	3.97	17480	13785	13670
Consumption for 1m^3 of mortar Kg. +/- 10%		305	244	216			
EN 459/BS 459 (mortar ratio 1:1 by volume, with ISO 679 Sand)							

Mixing: can be mixed in cement mixers.
Application by spray gun: possible. Please consult us.

Working temperatures: not below 5°C or above 30°C. Make sure that high suction materials are thoroughly dampened before application. Avoid rapid drying due to high temperatures or strong winds by curing with a light water mist several times a day if necessary. See *"Protecting Lime Mortar"*.

SUITABLE FOR LATH WORK / LIME CONCRETE/INJECTION/GROUTING See relevant sheets

Reworking: possible within 12 hours

Mortar composition: MASONRY/POINTING/ CAPPING/ BEDDING/ ASHLAR

Binder: sand ratio: from 1:1.5 to 1:3 depending on the support/background conditions, the size of the joint and the fineness of the sand. Always use well graded sands (3 - 4mm down to 75 microns).
See also *"Applications & Good Working Practices Sands for Lime Mortars"*.

RENDERING

A. Scratch coat (3-5mm) 1 VOLUME OF NHL 3.5 : 1.5 VOLUMES OF SAND - Cast on
B. Undercoat (15-20mm) 1 VOLUME OF NHL 3.5 : 2 VOLUMES OF SAND*
C. Finishing (5-10mm) 1 VOLUME OF NHL 3.5 : 2.5 VOLUMES OF SAND
With very fine sands possibly containing clays the binder content may have to be reduced.

*At this dosage the consumption is approx. 0.35kg. of NHL 3.5 per m^2 for each mm thickness.
Please also refer to *"Applications & Good Working Practices - NHL Renders."*

See *"Excell Certificate"*.

For further Guidance, contact your St Astier Distributor.

St. Astier NHL 5 Product Data: http://www.stastier.co.uk/nhl/data/nhl5.htm

Natural Lime NHL 5 (Chaux 100 naturelle Pure) Product Data
St Astier Natural Hydraulic Limes (NHL)

Conforms to European Norms EN 459 and BS 459
Strength factor: 5 (Eminently hydraulic)
Residue @ 0.09 mm: 7%
Density (volumetric weight) typical: 700 gr. / litre
Available (free) lime $Ca(OH)_2$ after slaking: 20-22%
Shelf life: 8-12 months kept sealed and dry

Contains no additives.
Whiteness index: 67
Surface cover (cm^2per gram): 8000
Expansion : < 1mm
Residue of quick lime after slaking: < 1%
Packing: 25kg. Bags

MORTARS	Compressive strengthN/mm^2				Elasticity Moduli (Mpa)		
MIX RATIO	EN459*	1 : 2	1 : 2.5	1 : 3	1 : 2	1:2.5	1 :3
7 DAYS		1.96	1.00	0.88	n/a	n/a	n/a
28 DAYS	5*	2.20	2.00	1.5	10800	1100	10000
6 MONTHS		7.31	5.91	5.31	18000	17050	16900
12 MONTHS		9.28	8.84	6.50	18510	17280	16150
24 MONTHS		10.81	8.81	7.8	21500	18020	17430
Consumption for $1m^3$ of mortar Kg. +/- 10%		350	280	233			
EN 459/BS 459 (mortar ratio 1:1 by volume, with ISO 679 Sand)							

Mixing: can be mixed in cement mixers.

Application by spray gun: possible. Please consult us.

Working temperatures: not below 5°C or above 30°C. Make sure that high suction materials are thoroughly dampened before application. Avoid rapid drying due to high temperatures or strong winds by curing with a light water mist several times a day if necessary. See *"Protecting Lime Mortar"*.

SUITABLE FOR LATH WORK / LIME CONCRETE/INJECTION/GROUTING See relevant sheets

Reworking: possible within 8 hours

Mortar composition: MASONRY/POINTING/CAPPING/MASS WALL BEDDING/ FOUNDATION/SEA DEFENCE WALLS/CHIMNEY STACS/NEW BUILD (Masonry)

Depending on the conditions of the support/background, the fineness of the sand and the size of the joints, binder : sand ratio values vary between 1: 1.5 to 1: 2.5

Choose well graded sands (3 or 4mm down to 75 microns).
See also "Applications & Good Working Practices - Sands for Lime Mortars".

RENDERING

A. Scratch coat (3 - 5mm) 1 VOLUME OF NHL 5 : 1.5 VOLUMES OF SAND Cast on recommended
B. Undercoat (15-20mm) 1 VOLUME OF NHL 5 : 2 VOLUMES OF SAND * (1:2.5 max)
*At this dosage the consumption is approx 0.4 kg. of NHL 5 per m2 for each mm of thickness
C. Finishing (5-10mm) USE NHL 3.5 OR NHL 2, see relevant sheets

For further Guidance, contact your St Astier Distributor.

FASZINATION KALK ...

OTTERBEIN

... SEIT JAHRTAUSENDEN BEWÄHRT ®

Technical Data Sheet

CALCIDUR® NHL 2

Natural Hydraulic Lime
EN 459-1 NHL 2

Mixing ratio for standard-type mortar in room sections:

Mortar group	CALCIDUR® NHL 2	Cement	Sand
Mortar			
II		-	3
II2		1	8
Plastering mortar			
PIc	1	-	3 to 4

Composition
CALCIDUR® NHL 2 is a natural hydraulic lime acc. to EN 459-1. It is produced through burning and staking a specifically selected shell limestone. The stabilizing process of CALCIDUR® NHL 2 is effected through carbonation and hydraulic hardening.
CALCIDUR® NHL 2 is free from cement!

Properties
- historic, cement- and gypsum-free natural hydraulic binder
- high sulphate resistance
- low-tension hardening process
- very good subsequent hardening properties
- no penetration of damaging salts into the masonry
- high elasticity and water retention capacity in mortar produced
- very good side adhesion at stone
- low elasticity module

Application
For the production of plaster- and brick mortar in ecological,biological building construction, in the restoration and preservation of historic buildings.

Delivery
In 25 kg bag
In big bag
In silo vehicles

Storage
Dry, if possible on wooden shelves and protected against draft. Storage time shall not exceed 6 months.

Technical data

Bulk density:	approx. 0.5 kg/dm³
free CaO:	approx. 35 %
SO_3:	approx. 0.4 %

Compression strength (acc. to EN 459-2):

28 days:	approx. 4.0 N/mm²
6 months:	approx. 6.5 N/mm²
12 months:	approx. 8.5 N/mm²

Safety instructions
CALCIDUR® NHL 2 reacts strongly alkaline with water, thus: Protect skin and eyes, rinse thoroughly with water in case of contact, immediately contact doctor in case of eye contact.

Quality-monitored production
CALCIDUR® NHL 2 is continuously tested in our plant laboratory within the scope of our in-house monitoring with respect to the fulfilment of composition and properties.
This will ensure a uniform quality of the product. CALCIDUR® NHL 2 has the quality certificate „Building lime“ and is certified acc. to EN 459-1.

FASZINATION KALK ...

OTTERBEIN

... SEIT JAHRTAUSENDEN BEWÄHRT ®

Technical Data Sheet

CALCIDUR® NHL 3.5

Natural Hydraulic Lime
EN 459-1 NHL 3.5

Mixing ratio for standard-type mortar in room sections:

Mortar group	CALCIDUR® NHL 3.5	Cement	Sand
Mortar			
II		-	3.5
II2		I	9
Plastering mortar			
PIc	I	-	3

Composition
CALCIDUR® NHL 3.5 is a natural hydraulic lime acc. to EN 459-1. It is produced through burning and staking a specifically selected shell limestone. The stabilizing process of CALCIDUR® NHL 3.5 is effected through carbonation and hydraulic hardening.
CALCIDUR ® NHL 3.5 is free from cement!

Properties
- historic, cement- and gypsum-free natural hydraulic binder
- high sulphate resistance
- low-tension hardening process
- very good subsequent hardening properties
- no penetration of damaging salts into the masonry
- high elasticity and water retention capacity in mortar produced
- very good side adhesion at stone
- low elasticity module

Application
For the production of plaster- and brick mortar in ecological,biological building construction, in the restoration and preservation of historic buildings.

Delivery
In 25 kg bag
In big bag
In silo vehicles

Storage
Dry, if possible on wooden shelves and protected against draft.
Storage time shall not exceed 6 months.

Technical data

Bulk density:	approx. 0.55 kg/dm^3
free CaO:	approx. 32 %
SO_3:	approx. 0.4 %

Compression strength (acc. to EN 459-2):

28 days:	approx. 4.8 N/mm^2
6 months:	approx. 8.5 N/mm^2
12 months:	approx. 10.5 N/mm^2

Safety instructions
CALCIDUR® NHL 3.5 reacts strongly alkaline with water, thus: Protect skin and eyes, rinse thoroughly with water in case of contact, immediately contact doctor in case of eye contact.

Quality-monitored production
CALCIDUR® NHL 3.5 is continuously tested in our plant laboratory within the scope of our in-house monitoring with respect to the fulfilment of composition and properties.
This will ensure a uniform quality of the product. CALCIDUR® NHL 3.5 has the quality certificate „Building lime“ and is certified acc. to EN 459-1.

FASZINATION KALK ...

OTTERBEIN

... SEIT JAHRTAUSENDEN BEWÄHRT®

Technical Data Sheet

HYDRADUR® NHL 5

Natural Hydraulic Lime
EN 459-1 NHL 5

Mixing ratio for standard-type mortar in room sections:

Mortar for stonework

Mortar group	HYDRADUR NHL 5	Sand
II		4.5
III		3
Plastering mortar		
PIIa	I	3 to 4

Composition
HYDRADUR® NHL 5 is a natural hydraulic lime acc. to EN 459-1. It is produced through burning and staking a specifically selected shell limestone. The stabilizing process of HYDRADUR® NHL 5 is effected through carbonation and hydraulic hardening.
HYDRADUR® NHL 5 is free from cement!

Properties
- historic, cement- and gypsum-free natural hydraulic binder
- high sulphate resistance
- low-tension hardening process
- very good subsequent hardening properties
- no penetration of damaging salts into the masonry
- high elasticity and water retention capacity in mortar produced
- very good side adhesion at stone
- low elasticity module

Application
For the production of plaster- and brick mortar in ecological, biological building construction, in the restoration and preservation of historic buildings.

Delivery
In 25 kg bag
In big bag
In silo vehicles

Storage
Dry, if possible on wooden shelves and protected against draft.
Storage time shall not exceed 6 months.

Technical data

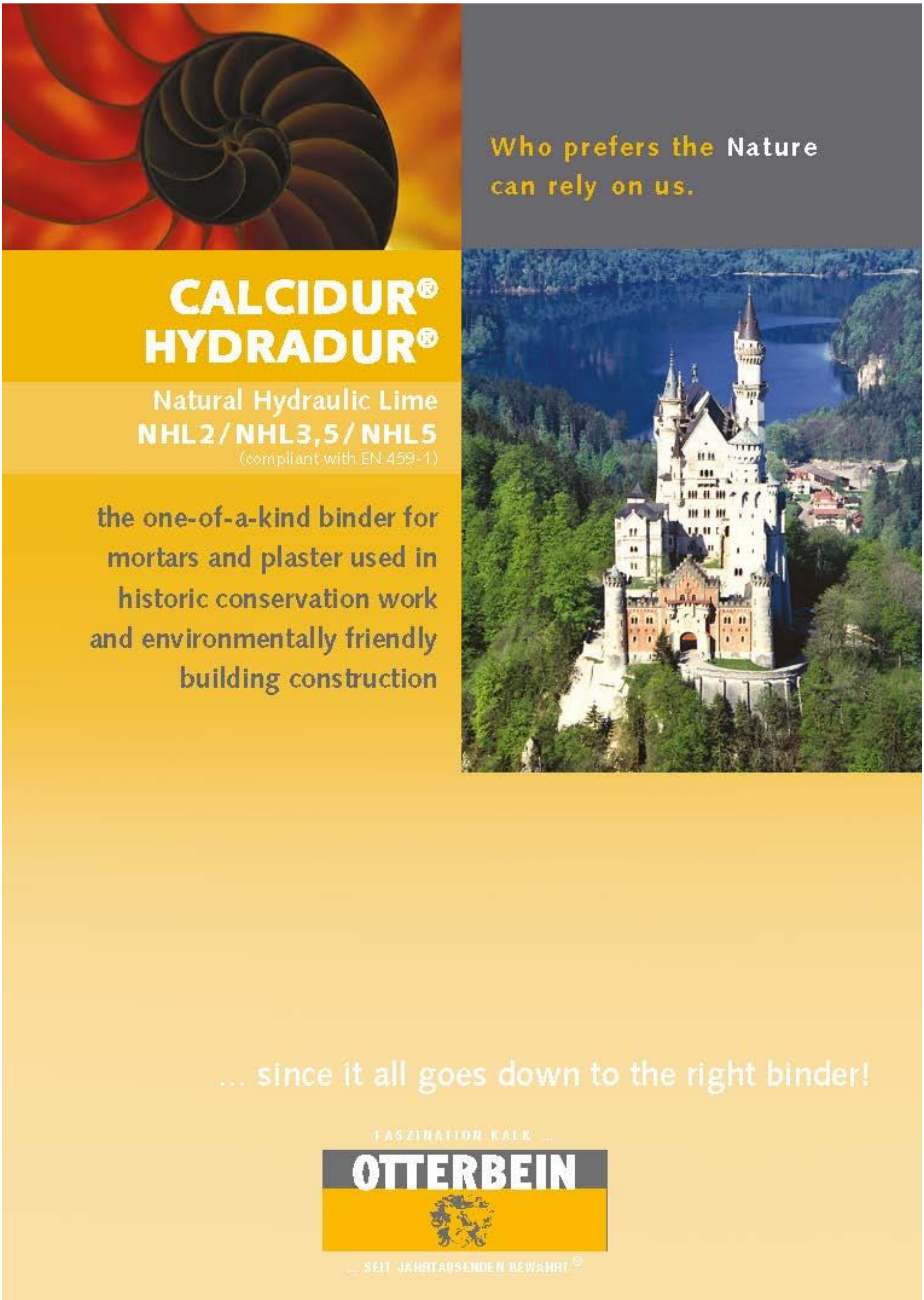
Bulk density:	approx. 0.55 kg/dm^3
free CaO:	approx. 30 %
SO_3:	approx. 0.5 %

Compression strength (acc. to EN 459-2):

28 days:	approx. 6.5 N/mm^2
6 months:	approx. 11.0 N/mm^2
12 months:	approx. 14.0 N/mm^2

Safety instructions
HYDRADUR® NHL 5 reacts strongly alkaline with water, thus: Protect skin and eyes, rinse thoroughly with water in case of contact, immediately contact doctor in case of eye contact.

Quality-monitored production
HYDRADUR® NHL 5 is continuously tested in our plant laboratory within the scope of our in-house monitoring with respect to the fulfilment of composition and properties. This will ensure a uniform quality of the product. HYDRADUR® NHL 5 has the quality certificate „Building lime“ and is certified acc. to EN 459-1.



Who prefers the Nature
can rely on us.
CALCIDUR®
HYDRADUR®
Natural Hydraulic Lime
NHL2 / NHL3,5 / NHL5
(compliant with EN 459-1)
the one-of-a-kind binder for
mortars and plaster used in
historic conservation work
and environmentally friendly
building construction
... since it all goes down to the right binder!
FASZINATION KALK ...
OTTERBEIN
... SEIT JAHRTAUSENDEN BEWÄHRT®

CALCIDUR®
HYDRADUR®

Natural hydraulic lime according to
European building lime standard EN 459-1

Lime mortar - tried and tested for centuries ...
... create objects with **CALCIDUR®/HYDRADUR®**

CALCIDUR®/HYDRADUR® from OTTERBEIN are:

pure lime binders

Their advantages:

- CALCIDUR®/HYDRADUR® are obtained from a unique natural lime-stone marl and do not contain any other additives
- CALCIDUR®/HYDRADUR® meet the stipulation to use materials according to the historical model when doing restorations
- CALCIDUR®/HYDRADUR® guarantee a high degree of resistance to environmental effects and ensure durability of the mortar made from them

flexible and easy to handle

Their advantages:

- CALCIDUR®/HYDRADUR® translate to ductility, good water retention and easy processing of the mortar because of their high air-hardening lime content
- CALCIDUR®/HYDRADUR® produce mortar that has optimum edge adhesion on stone

highly elastic

Their advantages:

- A low modulus of elasticity means optimum absorption of thermal and mechanical stresses

low cracking sensitivity when setting

Their advantages:

- The low cracking sensitivity when setting and natural and constant post-hardening minimize the risk of buildup of tension cracks in an effective and reliable manner
- The self-healing mechanisms of CALCIDUR®/HYDRADUR® minimize micro-cracking in mortar

The quality of the mortar used is a decisive factor when it comes to durability of masonry. The ancient Romans knew this fact. The natural hydraulic binders CALCIDUR®/HYDRADUR® are highly effective mineral building materials that bridge the ancient world and the 21st century.
Due to their strength, workability and authentic coloring, CALCIDUR®/HYDRADUR® are compelling materials especially for the restoration of monuments that are built to last.

Top: Durable masonry with CALCIDUR®/HYDRADUR®; Bottom: Damaged masonry because of wrong binder

left to right: Köpenick castle, Berlin; Neuschwanstein castle, Bavaria; Bad Hersfeld monastery ruins, Hessen

CALCIDUR®/HYDRADUR®
...investment in safety and strength!

The knowledge of innumerable generations of builders is collected in natural lime mortar. Its solidity and strength have outlasted historical buildings up to the present time. The Natural Hydraulic Limes CALCIDUR® (NHL2/NHL3,5) and HYDRADUR® (NHL5), made in compliance with European building lime standard EN 459-1, are free from additives and other binders. The singular composition of binders and the special combustion method impart CALCIDUR®/HYDRADUR® with authentic properties of traditional lime mortar. CALCIDUR®/HYDRADUR® are capable of counterbalancing the mechanical loads and physical/chemical stresses of masonry on a sustained basis and minimize the buildup of cracks. Moreover, the unique elasticity of lime mortar and the low cracking sensitivity during the hardening process translate to historical buildings that endure for a long time without any defects.

"As a restorer I am faced almost daily with the fatal consequences of incorrectly used building materials in historic conservation work. For this reason, I have been relying for years on CALCIDUR®/HYDRADUR®, because I can be sure that my work will endure and my client can count on durability and investment security."

Stefan Haustein, authorized representative and project manager of Bennert Restaurierungen GmbH

Landsberg castle, Meiningen

PRODUCT DATA SHEET

LIME

CI/SfB | Yq2 |

MAY 2011

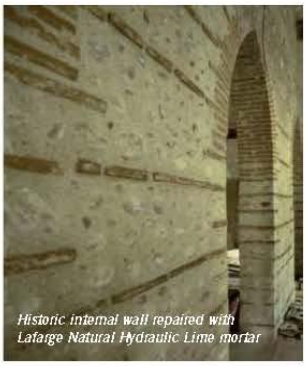
NATURAL HYDRAULIC LIME

EN 459-1: 2010 - NHL 2, NHL 3,5

LAFARGE
bringing materials to life™

Lafarge has a long and strong track record of producing Natural Hydraulic Lime stretching back to the mid 1800s. Since this time over 200 million bags (25kg) have been manufactured and used for a wide range of projects from renovating churches and castles to new build construction.
It is of high quality and manufactured from specially selected limestone containing clay and other impurities. This enables the material to set without exposure to air and even under water.

The Lafarge lime works in 1870



Historic internal wall repaired with Lafarge Natural Hydraulic Lime mortar

We offer the following range of products:

- **NHL 2**
  A feebly hydraulic lime suitable for internal works and exterior pointing/rendering on soft or crumbly masonry in sheltered areas
- **NHL 3,5**
  A moderately hydraulic lime suitable for general-purpose use for mortar/pointing/rendering of most masonry

Our products contain no additives, mineral additions or other binders and are quality assured to EN 459-1: 2010 Natural Hydraulic Limes with independent third-party certification. They also carry a CE Mark.

NATURAL HYDRAULIC LIME

Applications

Natural Hydraulic Lime can be used for both the conservation and renovation of historic buildings, and in new build applications. Mortars made with natural hydraulic lime gain strength by a combination of hydraulic setting and carbonation. The lower strength and greater permeability of natural hydraulic lime mortars when compared with cement-based mortars is particularly suitable for repairs to older buildings and for traditional style new build. Natural hydraulic lime mortars have good workability and plasticity and can accommodate some differential movement within the building.


A Grade II listed building in Warwickshire repaired with Lafarge Natural Hydraulic Lime mortar

Mortars

Typical hydraulic mortar mixes and their applications are shown below:

Application	Proportions (lime : sand by volume)	
	NHL 2	NHL 3.5
Internal walls	1:3	1:4
External walls	1:2	1:2 – 1:3
Facing to solid construction	1:2	1:2 – 1:3
Walls below ground	N/A	1:1 -1:2
Parapets, sills, lintels and cornices	N/A	1:2
Copings and cappings	N/A	1:2
Chimneys	N/A	1:1
Earth Retaining walls	N/A	1:1
Submerged masonry	N/A	N/A

Note: This information is for guidance purposes only. It is strongly recommended that trial mixes are carried out before use and that local exposure conditions are taken into account.

Renders

The selection of suitable render mixes, whilst following the guidance for mortars, must also consider the nature of the substrate to which the render will be applied. The type of sand used will also affect the final finish obtained. Guidance on selection of mixes for different substrates is given on the right.

Substrate	Proportions (lime : sand by volume)		
	Base Coat	Finish Coat	NHL Class
Weak or porous (soft brick)	1:2	1:2.5	NHL 2, NHL 3.5
Medium strength	1:2.5	1:2.5	NHL 2, NHL 3.5
Impervious or dense brick	1:2.5	1:2.5	NHL 3.5
Plasterwork	1:2	1:3	NHL 2, NHL 3.5

Note: As a general rule, each successive coat should be weaker and/or thinner as you move away from the substrate.

Batching and Mixing

Sand

Sand for lime mortars and renders should be sharp sand, clean and well graded, free of clay or silt. Building (soft) sands, or sands containing clay and silt, can cause excessive shrinkage.

Water

Mixing water should be clean and potable. Adding too much water should be avoided as it leads to a reduced strength and open structure susceptible to frost attack

Batching

Mortars and renders containing natural hydraulic lime should always be batched by volume using batch boxes.

Mixing

Sufficient mixing is required to ensure that the lime is uniformly dispersed throughout the mortar or render. Mechanical mixing is preferred and mixing times should be significantly longer than for cement-based mortar. The workability of the mortar improves with increased mixing time (however, avoid over mixing in hot weather). Allowing the mortar to stand in the mixer drum for a short period of time (10-15 mins) before a final remixing will also improve workability.

Working Temperatures

Do not use at temperatures below 5°C or above 30°C without taking precautions to protect new work from freezing or drying out.

Lafarge Natural Hydraulic Lime used for pointing new build construction

Use of Admixtures and Additions

The use of proprietary admixtures with natural hydraulic lime is not usually necessary as the workability and frost resistance of mortars or renders based on natural hydraulic lime is adequate for most applications.

In certain circumstances however, the addition of materials such as pozzolans or ground blastfurnace slag may be used to increase the mortar strength. The addition of Lafarge Hydralime (hydrated lime) can also be used to improve the plastic properties of the mortar and/or reduce its strength. Trial mixes are always recommended.

Storage

Lafarge Natural Hydraulic Lime should be stored in unopened bags clear of the ground in cool dry conditions and should be stacked in a safe and stable manner.

Information on the maximum storage period can be found on the bag.

Technical Support

Further information or specification advice on Lafarge Natural Hydraulic Lime and the full range of Lafarge Cement products can be obtained through the contacts listed on the following page.

Health and Safety

Contact between natural hydraulic lime and body fluids (eg, sweat and eye fluids) may cause irritation, dermatitis or burns. Natural hydraulic lime releases alkali when mixed with water, and the use of protective goggles, gloves and clothing during batching, mixing and application is recommended. For further information, refer to the Lafarge Health and Safety information sheet for Natural Hydraulic Lime.

Typical Key Properties (Not to be used for specification purposes)

Property	Lafarge NHL 2 Typical Value	Lafarge NHL 3,5 Typical Value
28 day Compressive Strength (MPa)	4.3	5
Initial Set (min)	330	350
Final Set (hrs)	8.7	8.5
Bulk Density (kg/m³)	615	590
Colour (L*)	89	90
Available lime (%)	43	44

BioLime NHL 2

TECHNICAL DATA SHEET

BioLime NHL 2 is eminently hydraulic natural hydraulic lime conforming to the requirements of EN459 1:2010. This Natural Hydraulic Lime (NHL) 2 is produced by low-temperature (1100^0C) calcination of calcareous marls. The traditional process involves firing, slaking, aging, and then grinding prior to final packaging. No extraneous materials or additives that would modify the natural composition of the original stone are used in production.

This authentically processed Natural Hydraulic Lime NHL 2 is used in the preparation of mortar for masonry, stucco and plaster. For architectural and historical applications, mechanical characteristics such as excellent porosity and low soluble salts ensure full compatibility with traditionally produced building materials (stone, solid brick, etc.). A high permeability to water vapor, ability to prevent bacteria and mold and optimal hygrothermal function ensures the achievement of high performance and durability, making this authentic Natural Hydraulic Lime NHL 2 an ideal binder for quality restoration work and Green Building.

PACKAGING AND STORAGE

The product is available in 25 kg (55-lb) Bags. Storage is intended to be in a protected, dry place.

AGGREGATE BLEND

Natural Hydraulic Lime 2 will typically be blended at a volume ratio of between 2 and 3 parts aggregate to 1 part NHL 2, depending on the desired strength and the granulometry of the aggregate. Pre-blended, color-matched, ready-to-use mortars, plasters and stuccos (requiring water addition only) are also available from Edison Coatings, Inc.

IMPORTANT: In order to preserve the unique characteristics of this material, there should be no added artificial hydraulic binders, particularly cementitious additives.

APPLICATION

Temperature: Both the ambient air and the substrate should be between 5°C (40°F) and 35°C (95°F).

Surface Preparation: Surfaces must be clean and free of any dust, oils, residues, bacteria, mildew, mold or other organic matter, salt efflorescence, or any other loose material.

Pre-Dampening: Before applying, moisten absorbent surfaces to reduce suction, but avoid ponding or complete saturation.

Pre-Hydration: To enhance the plasticity characteristics of the product, let the freshly mixed material stand for approximately 10-15 minutes prior to application.

Finishes: NHL 5 plasters may remain exposed directly to weather, or may be coated with compatible finishes. In order not to compromise water vapor permeability and natural appearance, use breathable finishes such as EverKote 300 Mineral Coatings.

Protection & Curing: Once applied, the product should be protected up to 48 hours from rain, frost and rapid drying due to direct sun or forced ventilation. Light periodic misting should be performed several times a day for the first 2-3 days.

TECHNICAL CHARACTERISTICS

PROPERTIES	**VALUES**
Appearance	Fine, white powder
Brightness	73.20
Fineness at 90µ	3.7%
Fineness at 200µ	0.1%
Apparent Density	0.619 kg/dm^3
Actual Density	2.52 g/cm^3
Blaine Fineness	11678 cm^2/g
Free Moisture	0.84%
Time of Setting - Initial	432 minutes
Time of Setting - Final	1458 minutes
Compressive Strength, 28 days	4.99 MPa
SO_3	0.84%
Free Lime	45%

REVISION: July 2017. This Technical Data Sheet supersedes all other prior editions.

Edison Coatings, Inc.

Exclusive North American Agent / Distributor
3 Northwest Drive, Plainville, CT 06062
Phone: (860) 747-2220 or (800) 341-6621 **Fax: (860) 747-2280 or (866) 658-1189**
E-mail: edisoncoatings@outlook.com **Internet: www.edisoncoatings.com**
BioLime, Inc. Product of FRANCE

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Edison Coatings, Inc.

BioLime® Natural Hydraulic Lime - NHL 3.5

BioLime® Natural Hydraulic Lime (NHL) 3.5 is designed for use in mortars and plasters for historical building restoration, quality building/construction and green building.

The product has a CE Certification and is in full compliance with UNI EN 459 1:2010, obtaining a registration mark as **NHL 3.5 (Natural Hydraulic Lime 3.5)**.

CHARACTERISTICS AND USE

Vignola Castello, Italy, restored with BioLime® NHL 3.5

This Natural Hydraulic Lime (NHL) 3.5 is produced by low-temperature (1100^{0}C) calcination of calcareous marls. The traditional process involves firing, slaking, aging, and then grinding prior to final packaging. No extraneous materials or additives that would modify the natural composition of the original stone are used in production.

This authentically processed Natural Hydraulic Lime NHL 3.5 is used in the preparation of mortar for masonry, stucco and plaster. For architectural and historical applications, mechanical characteristics such as excellent porosity and low soluble salts ensure full compatibility with traditionally produced building materials (stone, solid brick, etc.). A high permeability to water vapor, ability to prevent bacteria and mold and optimal hygrothermal function ensures the achievement of high performance and durability, making this authentic Natural Hydraulic Lime NHL 3.5 an ideal binder for quality restoration work and Green Building.

PACKAGING AND STORAGE

The product is available in 25 kg (55-lb) Bags. Storage is intended to be in a protected, dry place.

AGGREGATE BLEND

Natural Hydraulic Lime 3.5 will typically be blended at a volume ratio of between 2 and 3 parts aggregate to 1 part NHL 3.5, depending on the desired strength and the granulometry of the aggregate. Pre-blended, color-matched, ready-to-use mortars, plasters and stuccos (requiring water addition only) are also available from Edison Coatings, Inc.

IMPORTANT: In order to preserve the unique characteristics of this material, there should be no added artificial hydraulic binders, particularly cementitious additives.

APPLICATION

- **Temperature**: Both the ambient air and the substrate should be between 5°C (40°F) and 35°C (95°F).

- **Surface Preparation**: Surfaces must be clean and free of any dust, oils, residues, bacteria, mildew, mold or other organic matter, salt efflorescence, or any other loose material.
- **Pre-Dampening:** Before applying, moisten absorbent surfaces to reduce suction, but avoid ponding or complete saturation.
- **Pre-Hydration:** To enhance the plasticity characteristics of the product, let the freshly mixed material stand for approximately 10-15 minutes prior to application.
- **Application:** Recommended maximum thickness per application is not to exceed 2 cm (7/8" inch). Successive applications, for installations requiring additional thickness, should be made once the previous application has reached thumb-print hardness, following the same procedure.
- **Finishes:** NHL 3.5 plasters may remain exposed directly to weather, or may be coated with compatible finishes. In order not to compromise water vapor permeability and natural appearance, use breathable finishes such as EverKote 300 Mineral Coatings.
- **Protection & Curing:** Once applied, the product should be protected up to 48 hours from rain, frost and rapid drying due to direct sun or forced ventilation. Light periodic misting should be performed several times a day for the first 2-3 days.

TECHNICAL CHARACTERISTICS *

	Natural Hydraulic Lime NHL 3.5	**Standard UNI-EN 459-1:2010**
Density	0.7g/cm (~40 lb./cu.ft.)	
Color & Appearance	Fine powder, light brown/tan color	
Compressive Strength, 28 days	3.8 MPa (530 psi)	3.5 MPa (490 psi)
Residual at 0.20 mm	< 1%	≤2%
Residual at 0.09 mm	< 5%	≤15%
Stability	< 0.50 mm	≤2 mm
Content of free building lime	25%	≥25%
Content SO_3	< 1%	≤2%
Set time	8 h	≥1 h
pH (saturated sol. at 20°C)	12.3	
Flammability	Non-combustible	

*The above data were derived from laboratory measurements. This document is intended as a Technical Data Sheet for a specific product.

SAFETY

For complete information regarding correct storage, use and disposal methods and, please see **MSDS**. Lime is a naturally caustic (rapid absorption) material due to its high pH origin and creates an alkaline reaction when combined with water. Protect the eyes and skin from exposure. Keep out of reach of children. Dust may cause irritation to eyes, skin, nose, throat and upper respiratory tract. Avoid irritation by reducing exposure to dust. Use in a well-ventilated area or provide sufficient local ventilation. Do not ingest. If dusty, wear a NIOSH/MSHA- approved dust respirator. Wear eye protection. If eye contact occurs, flush thoroughly with water for 15 minutes. If irritation persists, call a physician.

FOR COMMERCIAL AND INDUSTRIAL USE ONLY

REVISION: October 2013. This Technical Data Sheet supersedes all other prior editions.

Edison Coatings, Inc.

Exclusive North American Agent / Distributor

3 Northwest Drive, Plainville, CT 06062
Phone: (860) 747-2220 or (800) 341-6621
E-mail: edison@edisoncoatings.com

Fax: (860) 747-2280 or (866) 658-1189
Internet: www.edisoncoatings.com
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BioLime NHL 5

TECHNICAL DATA SHEET

BioLime NHL 5 is eminently hydraulic natural hydraulic lime conforming to the requirements of EN459 1:2010. This Natural Hydraulic Lime (NHL) 5 is produced by low-temperature (1100^{0}C) calcination of calcareous marls. The traditional process involves firing, slaking, aging, and then grinding prior to final packaging. No extraneous materials or additives that would modify the natural composition of the original stone are used in production.

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PACKAGING AND STORAGE

The product is available in 25 kg (55-lb) Bags. Storage is intended to be in a protected, dry place.

AGGREGATE BLEND

Natural Hydraulic Lime 5 will typically be blended at a volume ratio of between 2 and 3 parts aggregate to 1 part NHL 5, depending on the desired strength and the granulometry of the aggregate. Pre-blended, color-matched, ready-to-use mortars, plasters and stuccos (requiring water addition only) are also available from Edison Coatings, Inc.

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APPLICATION

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Protection & Curing: Once applied, the product should be protected up to 48 hours from rain, frost and rapid drying due to direct sun or forced ventilation. Light periodic misting should be performed several times a day for the first 2-3 days.

TECHNICAL CHARACTERISTICS

PROPERTIES	VALUES
Appearance	Fine, light grey powder
Brightness	62.19
Fineness at 90µ	7.6%
Fineness at 200µ	1.2%
Apparent Density	0.769
Actual Density	2.64
Blaine Fineness	9837 cm^2/g
Free Moisture	0.58%
Time of Setting - Initial	183 minutes
Time of Setting - Final	401 minutes
Compressive Strength, 7 days	3.55 MPa
Compressive Strength, 28 days	8.02 MPa
SO_3	0.76%
Free Lime	26.7%

REVISION: October 2015. This Technical Data Sheet supersedes all other prior editions.

Edison Coatings, Inc.

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E-mail: edisoncoatings@outlook.com **Internet: www.edisoncoatings.com**
BioLime, Inc. Product of FRANCE

Schofield 180 White Mason Sand Product Data: Sieve Analysis

Since 1923

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Website: http://www.geoschofield.com
Email: sales@geoschofield.com

ocation: **PLANT 2 SOUTH** **Type:** 180 **WHITE MASON SAND**

ate: 8/10/2011
ime: 7:00:00
ustomer:
perator: JIM SCHWEIBINZ

ample Description:

Sieve No.	Mesh Size (mm)	Sieve Name	Cumulative Retained Weight (g)	Cumulative Retained Percent	Incremental Retained Percent	ASTM C - 144 Spec. for % Passing Min	ASTM C - 144 Spec. for % Passing Max	Cumulative Passing Weight (g)	Cumulative Passing Percent
1	4.75	4	0.0	0.0	0.0	100	100	528.0	100.0
2	2.36	8	0.1	0.0	0.0	95	100	527.9	100.0
3	1.18	16	23.0	4.4	4.3	70	100	505.0	95.6
4	0.60	30	171.0	32.4	28.0	40	75	357.0	67.6
5	0.30	50	403.9	76.5	44.1	10	35	124.1	23.5
6	0.15	100	515.3	97.6	21.1	2	15	12.7	2.4
7	silt & clay	*Pan	528.0	0.0	2.4			0.0	0.0

FM#	2.11

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- Golf Courses
- Landscaping
- Plastering
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- Roofing
- Wall Surfacing
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